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HETEROCHROMATIC PHOTOMETRY*

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(Translated by Karl K. Darrow)

1. Introduction

Since the earliest days of photometry, the observers have been confronted with the problem of heterochromatic photometry. As early as 1760 Bouguer, the father of photometry, remarked in his posthumous work[1] published in that year that the comparison of two lights of different colors is "embarrassing." Industrial photometry was fortunately exempt from these difficulties at its beginnings, which were contemporaneous with the beginnings of the gas industry; for the various sources—flame lamps—which had to be compared at that time were almost identical in color. A little later, attention was forcibly directed to the problem of heterochromatic photometry (which Bouguer had encountered in a difficult case, the comparison of the light of the sun with the light of a flame) by the introduction of a great variety of light-sources, such as the electric arc, the Welsbach mantle, and various incandescent lamps, into practical use. The remark about "embarrassment" of the earliest observer recurs in many articles devoted to this question. For example, Coblentz and Emerson, in a paper published in 1917 dealing with the spectral distribution of luminosity, in which they had occasion to utilize much previous work, mentioned that many

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[1] Bouguer: Traité d'optique sur la graduation de la lumiere. (Page 50 of the original edition). 1760.

observers thought that the equalization of two differently-colored fields was "guesswork that had no meaning." As a matter of fact, what strikes an observer at once when he is confronted with two very differently colored fields is the difference in quality between the two sensations, which do not seem to have any common measure.

We might thus be tempted purely and simply to reject the problem, as being insufficiently defined. But the problem, apart from what theoretical interest it may possess, presents itself as a practical and even as a commercial one. It *ought* to be solved, even if in a partly conventional manner. It is not necessary that every proposed solution be adapted to every imaginable case, nor be capable of solving every question without any previous knowledge of what is to be measured; it is sufficient to obtain, for every practical case, a solution which is acceptable, definitely accepted by common agreement, and not giving rise to conflicts.

The problem has been the cause of many researches, most of them performed in the United States, during the last few years. The International Illumination Commission considered it in its meetings at Paris in 1921 and at Geneva in 1924. Having been instructed, as Chairman of an international committee[2] designated by this Commission, to present a report on Heterochromatic Photometry, I will make use principally of the data contained in this report (of date 1924) and in a preceding report (of 1921) and likewise of the discussions which took place at these two meetings.

II. Physical Data Defining A Particular Radiation

The following circumstance is the first to strike the attention of anyone who tries to discern the present trend of research in heterochromatic photometry. While the early observers tried to solve each particular problem directly, by means of the eye and without introducing any information about the constitutions of the radiations to be compared, the contemporary investigators strive to take into account as many as possible of the physical data, apart from those due to visual perception, which characterize the radiations they compare. This evolution was very natural, but could occur only slowly. The data derived directly from the sense of sight, very complicated and encumbered with all the complexities of psycho-physiological phenomena

[2] Consisting of Messrs. Crittenden (U. S. A.), Rayner (Great Britain), Fabry (France). These reports will be found in the "Recueil des Travaux de la Commission Internationale de l'Eclairage" for the 1921 (Paris) and 1924 (Geneva) sessions.

as they are, were yet for a long period the only available data upon radiations and their intensities; delicate techniques had to be developed before it was possible to obtain results or even to make clear definitions, based on anything except visual sensations. Often the sense of these definitions is not perfectly understood, and it must be confessed that the language consecrated by use is sometimes responsible for many a misunderstanding. Consequently it will be useful to begin by recalling what is known (independently of the properties of the eye) about the spectral compositions of the various radiations in question.

"Energetic" definition of intensity.—Physically, every radiation should be considered as a mixture of 'simple' (monochromatic) radiations, each having a determinate wave length and a determinate intensity. This intensity should be defined by the quantity of energy which the radiation transports per unit time; it is of the same dimensions as power, and to be expressed in watts. We have only one direct method of measuring it: to transform the radiation into heat (which is always easily done by destroying it by means of an absorbing body) and determine the rate of production of heat.[3]

In the case of a source with a *discontinuous* spectrum, the complete analysis of the radiation will be represented by a table of the wave-lengths of the emitted monochromatic radiations, with the corresponding "energy values." In the (practically much commoner) case of a continuous spectrum, the radiation will be defined by its *energy-curve*, which gives the intensity as a function of the wave-length, in a normal spectrum. Representing by $E=f(\lambda)$ the equation of this curve, we have $f(\lambda)d\lambda$ as the power radiated in the form of radiations with wave-lengths between λ and $\lambda+d\lambda$.

It is very important to know this curve for every radiation used, particularly in the visible spectrum (from $\lambda=0.7\mu$ to 0.4μ approximately). Unfortunately, direct experimental determination of it is very difficult; delicate apparatus must be used, and handled with much critical sense; the immediate data obtained with the thermometric receiver require many corrections, to take account of the dispersion-

[3] The use of a thermometric receiver in this method of measurement, makes us sometimes forget that the *power* of the radiation is the quantity really measured; the name *calorific intensity*, often used to designate the result of the measurement so made, can easily cause wrong ideas. A radiation is not more particularly 'calorific' than e.g. an electric current; both transport energy, which may undergo various transformations, such as the transformation into heat which engineers know only too well. In measuring radiation by the thermometer, the transformation into heat is only a device for measuring the energy transported.

formulae of the prisms, of the incompleteness of the absorption by the receiving apparatus, of the selective weakening by absorption and reflection. Every one of the early measurements is worthless and even meaningless; correct measurements began to be made only about 1880, by Mouton and by Langley.

The study of a particular source becomes much easier if one has a *standard of spectral distribution of intensity* at his disposal. By this must be understood a source of which the energy-curve has been determined once for all, and which can be realized at will. The demands upon the constancy of such a source are not the same as those upon a primary standard of light-intensity, for the important feature is the ratio of the intensities of the constituent radiations, the scale remaining arbitrary. The acetylene flame, the black body at a known temperature, and to a certain extent the incandescent lamp, may be regarded as capable of being standards of this kind.

Once the energy-curve for any one standard source has been determined, the task of tracing it for any other radiation with a continuous spectrum is considerably simplified; being reduced to the making of a series of spectrophotometric comparisons between consecutive radiations of identical wave length, by means of the eye or by any other receiving apparatus.

Coblentz made a careful study[4] of the acetylene flame with regard to its function as a standard of energy-distribution. However, some slight uncertainty may still exist as to whether the spectra obtained with different burners are identical. It may be assumed that at present the best standard is that furnished by the radiation of the "black body," of which the importance stands out more and more conspicuously; together with the radiations from very hot solids, it deserves to be examined separately.

III. Radiation of the Black Body; Radiation from Incandescent Solids

The "black body" or complete radiator, consisting of an enclosure with uniform interior temperature, with a small aperture to let the radiation within it escape, is in a state completely defined by a single variable, its temperature.[5] The equation of the energy-curve of this radiation may now be regarded, owing to a long series of experimental

[4] Bureau of Standards Scientific Paper, no. 362, 1920.

[5] All temperatures are expressed, in this paper, in the absolute scale, indicated by the letter *K*—Kelvin's initial.

and theoretical researches, as perfectly known. It is expressed by Planck's formula:

$$E = A\frac{\lambda^{-5}}{e^{C_2/\lambda T} - 1}$$

which in most cases may be replaced by the simpler formula of Wien:

$$E = A\lambda^{-5}\, e^{-C_2/\lambda T}$$

Discussion of the recent measurements leads to the conclusion that Planck's formula represents the facts exactly, and the corrections to it which have been proposed are unjustified. The constant C_2 is the only one of interest from our present standpoint; according to Coblentz,[6] the most probable value for it is

$$C_2 = 14320 \text{ microns} \cdot \text{degrees}$$

Radiation of ordinary light-sources.—In most of our usual sources of light, the radiation is produced by a hot solid body yielding a continuous spectrum. The radiating body is not necessarily "black," hence nothing can be asserted a priori about its energy-curve. For a long period there was much uncertainty on this point, and certain measurements suggested that in all the usual cases the energy-curve is extremely different from the black-body curve. The recent researches however have shown that, except in some exceptional cases, the energy-curve is practically identical with the black-body curve for some particular temperature, at least in the visible part (in photometry, the only interesting part) of the spectrum. In other words, the energy-curve is simply the Planck curve for a suitable value of T.

This result is valid for all electric incandescent lamps (filament lamps) in their various operating conditions, and very probably for flames; it seems also to be approximately valid for daylight and for the light of the sky in all habitual conditions. The light of the Welsbach mantle is entirely different, and so likewise is (obviously) the light emitted in the form of discontinuous spectra by gases (flame arc, mercury arc, neon lamp).

Apart from some exceptional cases, the composition of light may thus be characterized by a single constant, *e.g.* the temperature of the black body yielding radiation having the same spectral constitution in the visible spectrum—the "color temperature." This temperature is not necessarily that of the incandescent filament, which is not a b'ack

[6] W. W. Coblentz: The present status of the constants and verification of the laws of thermal radiation in a heated enclosure. J.O.S.A.; *8* p. 11; 1924.

body; nothing proves that the brightness of the filament is that of the black body at the "color temperature," and in many cases it can be stated that these two brightnesses are very different. The color temperature is simply a parameter which, when inserted into Planck's formula, gives the observed energy-curve in the visible spectrum with sufficient accuracy. This temperature can be determined by bringing about equality between the colors of the radiation being studied and of a black body, and experiment shows that this process determines the "color temperature" with good precision.

Colorimetry and pyrometry of the black body.—The researches which led to the foregoing results[7] were in part carried out with regard to problems which fall outside of the province of this article although they are closely connected with heterochromatic photometry.

First: The problem of *colorimetry* (measurement and specification of color) has originated some important pieces of work in recent years, notably in America. This problem is, in a certain sense, complementary to our problem, which is the problem of defining the intensity without regard to the color, for it involves defining the color without any regard to the intensity. However, it is unreasonable to wish to compare complex radiations while remaining systematically ignorant of everything pertaining to their spectral composition, and hence to their color. The advances in colorimetry have contributed much to progress in heterochromatic photometry.

Second: *Pyrometry*, for very high temperatures, is altogether a question of radiometry, and has borrowed many of its methods from photometry and colorimetry; in turn it has had great influence in these two fields. In particular, the available information about the energy-curves of the ordinary sources is due, in part, to measurements made for purposes of pyrometry; the very important conception of "color temperature" originated from the same researches.

Sunlight and daylight.—These forms of light possess continuous spectra; though they are obviously of practical importance, there are few spectrophotometric data on the light which reaches us from the

[7] For the details of these researches, see the following references: W. E. Forsythe: Color match and spectral distribution. J.O.S.A. *7*, p. 1115; 1923.

Forsythe & Worthing: The properties of tungsten and the characteristics of tungsten lamps. Congrès de Genève, 1924.

Buckley, Collier & Brookes: Report of work carried out at the National Physical Laboratory. Congrès de Genève, 1924.

L. T. Troland: Report on colorimetry. J.O.S.A., *6*, p. 527; 1922.

Forsythe: Report on pyrometry. J.O.S.A., *5*, p. 494; 1921 and *4*, p. 305; 1920.

sun, whether directly across the atmosphere, or by various kinds of scattering. The very extensive measurements of Abbot were made with especial regard to the radiation *emitted* by the sun, rather than what *we receive* under ordinary conditions. I shall speak further on of the purely colorimetric measurements of Priest; they led to this result: in every case, the color of "natural" light can be matched by a radiation having the Planck energy-distribution, with a suitable value for the temperature. Although this does not prove that the two radiations have the same spectral composition, it is still possible to speak of the "color temperature" of sunlight or daylight.

Utility of additional and more extended measurements.—In the foregoing pages it is shown that important progress has been made in the study of the radiations which we use for illumination. However, still further researches are to be desired. The recent investigations relate only to the visible spectrum, in fact exclusively to the central part of this region, which is the only part of real importance to photometry. For other purposes it would be of interest to have data extending over a much wider spectral range, including the infrared and the ultraviolet. Such data would often be of use to physicists who have to measure radiations; they would furnish a solid foundation for the investigations of physiologists upon the injuriousness of various sources of light. Such a foundation seems to be entirely missing in many discussions.

IV. Criterion for Equality in Direct Comparisons of Radiations Differing in Color

There exist well-known methods for varying, in preassigned proportions, the radiations received upon a screen; every photometric problem is reducible to an equalization of two photometric fields. In the case of homochromatic photometry, this equalization is performed with an accuracy superior to 1%. Whatever criterion be used, this accuracy is diminished when the colors of the fields are not the same. Further we find this grave difficulty: certain observers obtain results distinctly different from those which most observers give. We are led to solve the question, not by taking the average of the results obtained by all the observers, but by simply eliminating the "abnormal" observers. Thus we resolve a question of numerical measurement *by adopting the opinion of the majority*, which is generally regarded as scarcely a scientific method. Yet this procedure is legitimate in this case, for we are

concerned with judging the value of a kind of light for the greatest number of individuals.

The different methods of direct heterochromatic comparison differ in the criteria adopted to judge the equality of brightness of the two photometric fields. The proposed methods are the following:

1. *Direct attempt to estimate equal brightness.* The observer tries to ignore the difference in color between the two fields, in order to decide when they seem equally illuminated to him. A variant of this method is the use of the contrast photometer.

2. *Method of equal visual acuity.* Two illuminations are considered equally bright when they enable the observer to perceive the same details, which gives them the same value for practical purposes.

3. *Flicker method (flicker photometer).* On a single field, the two radiations to be compared are projected alternately at a given frequency; the brightnesses are considered equal when the impression of flicker vanishes.

4. *Critical frequency method.* There is a single photometric field, the illumination of which is periodically cut off. By augmenting the frequency of the eclipsings, a critical frequency where the flicker vanishes is reached. This frequency is lower, the fainter the light; two brightnesses are regarded as equal if their critical frequencies are the same.

5. *Pulfrich stereo-spectral-photometer.*[8] On a bright background, a dark band is displaced back and forth, in a straight line perpendicular to the line of sight. If the illuminations perceived by the two eyes are unequal (e.g. if one eye is covered by an absorbing glass) it seems to the observer that the band moves not in a line but around a cylinder; the sense of this apparent rotation changes when the light going to the other eye is made the feebler, and the apparent movement becomes rectilinear when the illuminations perceived by the two eyes are equal. The effect is due to the lapse of time between excitation and perception, which varies with the intensity of the radiation.

Of these methods, the one based on visual acuity is not sufficiently accurate to be of real use. The critical-frequency method is based on a very artificial criterion. As to the stereophotometer, it is not yet possible to say whether it will be of any service.

The modern results are based exclusively upon the method of equal brightness (with or without contrast) and the flicker method. The

[8] Zs. f. Instrumentenkunde, *42*, p. 56; 1922.

experimental conditions necessary for coherent results have been carefully studied of late years.[9]

Under such conditions, there seems to be no systematic difference between the results obtained by the two methods—which was not by any means certain a priori, the two criteria for equality being very different. As for the accuracy of measurements, the method of direct equalization is distinctly superior when the colors are the same or not very different, while the flicker method excels when the two fields differ greatly in color.

The present tendency seems to be to adopt the flicker method in researches in which it is necessary to compare two very different lights. As will be seen further on, such comparisons are more and more being restricted to special researches, as those on the sensitivity-curve of the eye; practical photometry is more and more being reduced to almost homochrome comparisons for which the method of direct equalization is both simpler and more accurate.[10]

All heterochromatic comparisons may be impaired by the Purkinje phenomenon. When this phenomenon is appreciable, it deprives of significance even the conception of a measurable ratio, for two seemingly-equal brightnesses cease to be equal when multiplied by one and the same factor. The Purkinje effect becomes enormously important when the two brightnesses to be compared are very weak and also very very different in color (like those of the nocturnal sky and of our lamps). Photometric measurements should be made under conditions in which this effect does not enter. This is the case whenever the photometric screen receives a sufficient illumination, exceeding for example some ten lux. However, cases may occur in which it is impossible to eliminate the Purkinje effect; for example, when it is desired to express the brightness of the night sky in ordinary photometric units, which are defined in terms of a standard lamp. The conventions to be adopted in order to give significance to such measurements have never been defined, and should be made the object of careful examination.

[9] See for this subject E. C. Crittenden: Heterochromatic photometry. Commission internationale de l'éclairage. Reunion de Paris, 1921.

[10] This explains why there are scarcely any flicker photometers constructed in a commercial way. I must however mention the following ones, lately developed: 1. An apparatus of the classic type with rotating sector, which can be adjusted upon the usual photometric bench; this is by Guild. A new flicker photometer for heterochromatic photometry, Jl. Sci. Instr. *1*, p. 182; 1914. 2. A rotating polarization apparatus, by Yvon. Revue d'Optique, *1*, p. 498; 1922.

V. DATA ON THE SENSITIVITY OF THE EYE

Much progress has been made in recent years in ascertaining these data, especially for large values of brightness, which are not affected by the Purkinje phenomenon. They were long considered to be of interest only to physiologists, and played no part in the earlier development of photometry. Nowadays the situation is changed, and these data can be used in solving very many problems of practical importance.

Let us begin by defining the quantities which are to be determined. These quantities present themselves automatically to the attention, when a particular radiation is studied both in regard to its energy distribution and in regard to the visual impression it makes.

Consider a radiation, simple or complex; represent by W the power (in watts) which it transports. As regards its luminous quality, it is characterized by a certain "luminous flux" F, to be expressed in lumens. If the spectral composition of the radiation remains constant, F and W are proportional to one another, and we can write

$$F = LW$$

L may be called the "visibility coefficient" of the radiation under consideration. It depends solely on the spectral composition of the radiation, both in the invisible and in the visible part of the spectrum.

The same definition is applicable, in particular, to a monochromatic radiation; for a given wave-length λ the coefficient L has a value L_λ which is a function of λ; the curve representing L_λ as function of λ has a maximum at a wave-length close to 0.55μ. It is convenient to compare the various values of L_λ with the value L_0 corresponding to λ_0. We set therefore

$$L_\lambda = L_0 K_\lambda$$

The numerical factor K_λ is the "coefficient of relative visibility" for the radiation λ; its value is unity for $\lambda = \lambda_0$, less than unity for all other radiations.

L_0 represents the number of lumens corresponding to one watt radiated in monochromatic radiation of wave-length 0.55μ. Its reciprocal is the number of watts necessary to produce a flux of one lumen in radiation of the same kind. This last quantity is often given the distinctly improper name "mechanical equivalent of light."

The study of the properties of the eye is thus reduced to the two following problems:

1. Study of the values of K_λ for all radiations, and tracing of the "curve of relative visibility" giving K_λ as a function of λ;

2. Measurement of L_e or its reciprocal, the "mechanical equivalent of light."

Only the former of these has a real importance in questions of heterochromatic photometry.

Curve of relative visibility.—The early measurements upon the relative luminosity of the different regions of the spectrum are meaningless, as they are not accompanied by data nor even by correct definitions regarding the energy-intensities; the precise meaning of the problem did not begin to be understood until the classical work of Langley. Of recent years the purely physical part of the problem (the energy-measurements) has been suitably solved, and observers have been able to devote their chief efforts to the photometric comparison. Two different methods have been used; I give outlines of them, as follows:

(a) The illuminations produced by the various monochromatic radiations are compared one by one, each having a known energy-intensity, with a photometric field which is the same (generally white) in every case. The measurements on the various monochromatic radiations are then independent of one another, and cannot be subject to cumulative errors; but the two photometric fields are violently different in color, and the comparison is affected by the usual uncertainties affecting comparisons of extremely different colors. The flicker photometer is generally used.

(b) The observer goes *step by step* along the spectrum; a certain monochromatic radiation is compared with one of slightly greater wave-length, this with a third, and so forth, until the whole spectrum is covered. Each comparison is almost homochromatic and the method of direct equalization may be used; but the final result is deduced from a long series of successive comparisons, the errors of which may to some extent be cumulative.

To eliminate the influence of the peculiarities of individual eyes, it is desirable to use measurements made by a great number of persons, throwing out the "abnormal" observers. Thus Coblentz and Emerson used 125 observers in their measurements.

I cannot here enter into the details of the series of observations made by one or the other of the methods which I have just mentioned.[11] It will suffice to say that the measurements agree well enough to permit

[11] In this connection cf. the two following reports to the International Illumination Commission: E. P. Hyde: La fonction de visibilité relative et l'équivalent mécanique de la lumière. Session de Paris; 1921. K. S. Gibson: The relative visibility function. Session de Genève; 1924.

us to feel that the data are definitely known, except perhaps at the extremities of the spectrum. All the measurements, however, relate to intensities of illumination sufficiently high to escape the Purkinje effect; the case of weak illuminations is not covered.

The following table gives the values proposed by Gibson and Tyndall, based on their own and on previously-published determinations. The Geneva congress adopted these values as the ones which should be used in all calculations, pointing out however that they may be erroneous in the extremities of the spectrum, or in very special conditions of brightness of the field and of the region surrounding the field.

Wave length in mμ	Relative Luminosity	Wave length in mμ	Relative Luminosity
400	0.0004	590	0.757
410	.0012	600	.631
420	.0040	610	.503
430	.0116	620	.381
440	.023	630	.265
450	.038	640	.175
460	.060	650	.107
470	.091	660	.061
480	.139	670	.032
490	.208	680	.017
500	.323	690	.0082
510	.503	700	.0041
520	.710	710	.0021
530	.862	720	.00105
540	.954	730	.00052
550	.995	740	.00025
560	.995	750	.00012
570	.952	760	.00006
580	.870		

Knowing the curve of relative luminosity, we can solve by calculation certain problems of heterochromatic photometry from purely homochromatic measurements. Let me cite the following ones, which are directly solved by a graphical integration:

(1) To determine the transmission-factor of a colored screen, for a complex radiation of known energy-distribution. It suffices to have determined the transmission-factor for the different monochromatic radiations (spectral transmission-curve) which is a problem of spectrophotometry requiring only homochromatic measurements.

(2) Given two sources differing in color, their energy-distribution curves being known; to determine the ratio of their intensities, starting

from a comparison made through a sensibly monochromatic filter, or even through a colored filter of known transmission-curve.

Mechanical equivalent of light.—The first measurements of this quantity produced extraordinarily discordant results; not until fifteen years ago was its order of magnitude known with any degree of precision. The recent measurements have been made by two methods.

(a) Monochromatic light of wave length 0.55μ is used, and the power and the luminous flux are measured directly. By this method Buisson and Fabry obtained, in 1911, the first reasonably exact value (0.00145 watts per lumen); subsequently other observers used it. It is as direct as possible, the energy-measurement is easy, but the visual measurement (comparison of a green monochromatic light with the white standard) is a very pronounced instance of a heterochromatic comparison.

(b) A continuous-spectrum radiation is used, having a color similar to that of the light-standard; its energy-distribution curve is independently determined; having in addition the curve of relative luminosity (vide supra) we have all the data necessary for solving the problem.

The exact value should be taken as approximately 0.0016 watt per lumen.

Knowing the "mechanical equivalent of light" and the visibility-curve, we could pass without any process of a photometric nature from energy-data to photometric data; but we cannot yet dream of introducing such a procedure into practical work. Up to the present time energy-measurements have been and still remain auxiliary to photometric measurements, without supplanting these.

VI. METHOD FOR AVOIDING HETEROCHROMATIC COMPARISONS IN ROUTINE PHOTOMETRIC PRACTICE

Until very lately all measurements of practical photometry were made by direct comparison with the intensity-standard; the difficulties encountered when the colors are very different are remarked in many articles upon photometry.[12] The present-day tendency, however, is to confine the heterochromatic comparisons as far as possible to research laboratories specially equipped for them, and to devise methods which make it possible, after suitable investigations performed once for all, to

[12] See for example Broca, Jouaust, de la Gorce, and Laporte: Etude des nouvelles lampes electriques luminescentes, etc. Bull. soc. electriciens *3*, 3; p. 101; 1913.

reduce all the measurements to homochromatic comparisons. There is also a tendency to make a thorough study of the cases which actually occur in practice: that is to say, to devise methods applicable to sources with continuous spectra more or less similar to the black-body spectrum, leaving out of account the oddly-colored sources like the mercury and neon lamps which are, on the whole, of almost negligible interest. The methods which have been proposed or tried are already numerous and varied; as it is difficult to say which of them will finally be used in practice, it will be worth while to review them all.

Photometry of the black body by means of so-called monochromatic filters.—The notion of basing heterochromatic comparisons upon measurements made through one or more "monochromatic" filters is quite old; it had no solid foundation so long as the composition of the radiations under study was unknown. Conditions changed when the energy-curve of the black body was determined. The composition of every radiation of the black-body type is defined by a single variable, *e.g.* its color temperature. Suppose, then, we have to compare such a radiation with the radiation of a standard source, having likewise a black-body spectrum. The color-temperature of this standard source may be supposed to be known. If we know likewise the color temperature of the source under study, a single comparison through a monochromatic filter should in theory suffice to fix the ratio of intensities. On the other hand, if we know nothing about the color temperature of the latter source, two comparisons made upon two monochromatic constituents of the radiations are necessary and sufficient. These two cases correspond approximately to the methods of Crova and of Macé de Lépinay, which should be examined in the light of our present knowledge.

Method of measuring with a single filter.—Crova proposed to compare any pair of sources whatsoever by using a filter transmitting only radiations close to 582 mμ; the ratio obtained should, according to him, represent the true ratio of the intensities of the two sources. Ives and Forsythe have already pointed out that this method cannot give exact results in all cases, if the temperatures of the two sources are very different. Boutaric and Vuillaume[13] reinvestigated the question, by making calculations based upon the black-body energy-curve and the visibility-curve. For each temperature they compute the ratio r/p

[13] Boutaric and Vuillaume: Sur quelques propriétés des sources lumineuses à rayonnement intégral. Revue d'optique, *2*, p. 41; 1923.

between the total luminous intensity and the intensity within an infinitely narrow region at 582 mμ; since the relative (not the absolute) values of this ratio are the significant ones, I give their results multiplied by a constant factor in the following table:

Absolute temperature	$z = Kr/p$
1600°	1.02
2000°	1.01
2200°	1.00
2400°	1.01
2600°	1.02
3000°	1.05
4000°	1.12
5000°	1.17
6000°	1.22
8000°	1.29
10000°	1.35

The quantity in the second column would be constant if Crova's method were applicable in every case; we see that this is far from true at the very high temperatures corresponding to natural light. If we know the color temperatures of the two radiations being compared, we can calculate the true ratio of the intensities from the comparison at 582 mμ.[14]

Unfortunately the Crova filter is a very poor approximation to the monochromatic filter postulated in these calculations. Jouaust studied this question, and a report upon his researches was made at the Geneva conference. The spectrophotometric study of the Crova filter shows that it is far from being a monochromatic filter; the transmission-factor exceeds 0.7 (in terms of its maximum value as unity) all the way from 525 to 588 mμ; consequently the calculations based on the supposition of monochromatic light lose much of their interest. Jouaust also made trials of direct comparison between carbon-filament lamps and gas filled lamps with the Crova filter; the somewhat unexpected result is, that the filter neither abolishes nor even diminishes the differences in the comparisons as made by different observers. Each ob-

[14] Boutaric and Vuillaume propose a formula involving the ratio of brightnesses of the two sources. It should be pointed out that the photometric comparison does not give this ratio by any means; it would be a difficult thing to measure for an incandescent lamp. Furthermore, to reach their formula the authors reason as though the two sources had all the properties of the black body, both as regards spectral composition and as regards brightness. This hypothesis is not justified at all in most cases.

server gets sensibly the same readings whether he make the comparison directly with the entire radiation, or with the radiation transmitted through the filter; but the difference between the values obtained by two observers may run as high as 7%.

It seems therefore that the Crova method, in its original simple form, cannot give an acceptable solution of the problem; some other scheme for producing a monochromatic filter will have to be found. As this condition of monochromatic transmission cannot be exactly realized, it will be necessary to determine the transmission-curve of a given filter, and make calculations similar to those of Boutaric and Vuillaume, taking account of all the radiations of which a measurable amount is transmitted.

Method of measurement by two radiations (*Macé de Lépinay*).—The source under study is compared with the standard, through two monochromatic filters—a red one transmitting 630 mμ and a green one transmitting 530 mμ—in succession; the ratio of the luminous intensities of the two sources is deduced from these measurements by an empirical formula. This scheme is certainly practicable *if*: (1) the standard source always has the same spectral composition; (2) the source under study emits a radiation of the black-body type, defined by a single variable.

The Macé de Lépinay formula was determined by direct comparisons with a Carcel lamp. Boutaric and Vuillaume made calculations to test it, assuming 2000° K. as the equivalent temperature of the Carcel lamp, and assuming that the filters were perfectly monochromatic.[15] They found that the Macé de Lépinay formula gives exact results for a source at 2000° (of course) and also for a source at 4300° K. At intermediate temperatures the error goes as high as 12%, this occurring at 3500° K.; it would reach 27% with a source at 6000° K.

Boutaric and Vuillaume proposed a formula which is more general (being applicable to any standard emitting radiation of the black-body type), simpler, and more exact. Representing by θ the color temperature (in the absolute scale) of the source used as standard; by V and R the data obtained by the comparisons using the green and red filters, respectively; and by I the desired ratio of the total intensities of the two sources, we have

$$I/R-1=2\cdot 10^{-4}\theta(V/R-1)$$

[15] Revue d'optique, *2*, p. 41; 1923.

The differences between the values directly obtained and the values given by this formula are said not to exceed 1%.

Unfortunately we do not know the transmission-curves of the filters employed by Macé de Lépinay; they probably are but very imperfect approximations to monochromatic filters. The question should be studied more thoroughly, either by direct experiment or by calculations based upon the transmission-curves.

The colored filters do not constitute the only form of apparatus which might be used for the study of light-sources in monochromatic light. The "monochromatic telescope" long since described by Lord Rayleigh[16] deserves a trial.

Photometry by equalization of colors.—Given a radiation with a continuous spectrum, we can always imagine a mode of attenuating its constituent monochromatic radiations in such proportions that its energy-curve will assume any preassigned shape. If therefore we have a standard source A of determinate spectral composition, we can transform its energy-curve *by subtraction* into a curve which (relative values only being considered) can be superposed upon the energy-curve of any other source B. The comparison of B with the thus-modified A is a homochromatic comparison, which can be made with great exactness. To deduce the ratio of B to A from this comparison we need to know only the ratio of the luminous intensities of modified A and of unmodified A; in other words, the *attenuation-factor* of the filter which is interposed to modify A. The determination of this factor involves heterochromatic comparisons more or less directly; but once it is effected, all measurements upon radiations of the same composition as B will be performed by homochromatic comparisons; the difficult part of the problem is thus solved once for all at the beginning.

It is not absolutely necessary that the energy-curve of A be modified so as to agree exactly (apart from the constant factor) with that of B; this indeed could not be done by any simple means; it suffices to make the two colors identical, and if when this is done the energy-curves are not too much different, the two colors will be identical for slightly abnormal eyes as well as for normal ones.

In using this method it is presupposed that the transmission-factor of the color-modifying filter has been determined once for all. This can be done in either of two ways:

[16] Lord Rayleigh: A monochromatic telescope with application to photometry. Phil. Mag. *19*, p. 446; 1885 and Scientific Papers *2*, p. 420.

(a) By direct comparison of the intensity of the source received directly and through the filter. The heterochromatic comparison is not evaded, but is made once for all.

(b) By determining the transmission-factor of the filter for each monochromatic radiation (homochromatic measurements with the spectrophotometer); knowing the spectral energy-curve of the source and the visibility-curve, we calculate the integral transmission-factor of the filter, for the radiation in question. The heterochromatic measurements thus enter only into the experiments made in determining the visibility-curve.

The methods proposed for modifying the color of the radiation are quite diversified. I will give an outline of them.

Use of colored liquids.—By interposing two strata of different liquids, of which the thickness and the concentration can be varied in the path of the radiation from the standard source, it is possible to modify the radiation to any color whatever (within certain limits).

I proposed this method in 1903[17] and gave a more detailed account in 1913.[18] The liquids were: an ammoniacal solution of copper sulphate (blue liquid) and a solution of iodine and potassium iodide (yellow liquid). The standard source was a Carcel lamp; the radiation of such a lamp is not very different from that of a carbon-filament lamp. The attenuation-factor can be ascertained once for all as a function of the thicknesses or the concentrations of the two liquid strata. For routine measurements it is sufficient to choose the thicknesses giving the desired color, and then to apply the corresponding attenuation-factor, derived from the empirical formula previously determined once-for-all; the comparisons are perfectly homochromatic. For all sources having continuous spectra similar to the black-body spectrum (from candle-light to sun-light) the blue liquid by itself is enough to modify the color of the source to the desired color with remarkable precision; the two liquids together are required for other cases, such as the mercury lamp and the Welsbach mantle.

Other liquids have been suggested subsequently. Yet the use of liquid absorbents seems not to have become general, in spite of its great advantage of enabling the transmission-factor to be ascertained from investigations made *once for all* upon the particular liquids

[17] Sur une solution pratique du probleme de la photometrie heterochrome. C. R. *137* p. 743; 1903.

[18] A practical solution of the problem of heterochromatic photometry. Illum. Eng. Soc.; June 1913.

utilized. It must be admitted that liquid filters are not extremely agreeable to use in practice, and demand certain precautions. One must watch out for evaporation, and errors may occur if the walls of the cell are not kept clean. Finally, the influence of temperature upon the absorption may be perceptible, and should be investigated; likewise the durability of the liquids. In spite of these little difficulties, it may be believed that by using well-studied liquids a very convenient solution of the problem of heterochromatic photometry could be achieved.

Use of solid color-filters.—Fewer precautions are required when a solid filter is used, but in this case the transmission-factor must be determined for each individual filter anew, either directly or by comparison with a similar filter already calibrated. As solid filters we may use colored glasses (colored throughout the volume of the glass), or gelatine films (with or without glass support) tinted with colored substances; the second device gives more latitude in the selection of colored substances, but less confidence in the durability of the filters. The values of the attenuation-factor, for a particular well-determined standard, can be ascertained by the methods mentioned in dealing with liquid filters; each solid filter should be provided with its spectral transmission-curve, which is a perfectly definite datum, independent of the properties of the eye and comparatively easy to determine; this curve would be extremely useful in such computations as one might have to make concerning the filter.

The use of colored glasses (usually colored with cobalt blue) to modify the color of the radiation from standard sources, is already widespread in photometric laboratories. For example, the light of the carbon-filament lamp may be altered, by filtration through blue glass, so as to display the color of the lamp (evacuated or gas-filled) with tungsten filament. By interchanging the filters used by different laboratories, the different values of transmission-factor used in them can be compared and the measurements made in them can be harmonized.

Method based on the rotatory dispersion of quartz (Priest).—The relative intensities of the different monochromatic constituents of a composite radiation, and consequently its color, can be altered in many other ways than by selective absorption. Priest has suggested utilizing the well-known phenomenon of rotatory polarization displayed by quartz, and

presents his scheme[19] as a complete and satisfactory solution of the problems of visual photometry and colorimetry of all the radiations conforming in spectral distribution (approximately, at least) to Planck's formula; these including the light of every sort of incandescent lamp, of the sun direct or through clouds, of the moon, of the sky, and (in some cases) the light diffused by certain walls.

Starting with an incandescent lamp operating under fixed conditions (these fixing the spectral composition of its radiation) we alter the light from it by the known scheme of utilizing the rotation of plane of polarization produced by quartz. The light passes through two polarizers, between which there is placed a plate of quartz cut perpendicularly to its optic axis. Owing to the varying extent in which the different monochromatic constituents of the light suffer rotation of their planes of polarization, they emerge with different degrees of attenuation, which are easy to calculate. Represent by e the thickness of the quartz plate; by α_λ the rotatory power of quartz (per unit thickness) for radiation of wave length λ; by ϕ the angle through which one of the polarizers is twisted, measured from the position in which the light is extinguished and in the sense in which the plane of polarization is rotated by the quartz. The transmission-factor for the radiation λ is then

$$F_\lambda = A \sin^2(\theta - e\alpha_\lambda)$$

A being a constant, sensibly independent of λ, in which allowance is made for the transmission-factors of the polarizers and of the quartz plate. As α_λ is a known function of λ, F itself depends upon λ and can be computed with great exactness. Representing by $I = \psi(\lambda)$ the energy-curve of the source, we have $I' = F\,\psi(\lambda)$ for the energy-curve of the light after traversing the apparatus.

Priest finds that, with a source having the black-body energy-curve corresponding to some particular temperature, and with suitable choice of e and ϕ, it is possible to reproduce, pretty exactly throughout the visible spectrum, the black-body curves corresponding to all other temperatures within a rather wide range. He always uses a quartz plate 0.5 mm thick ($e = 0.05$ cm); but different standard sources for different cases, as follows:

[19] I. G. Priest: The colorimetry and photometry of daylight and incandescent illuminants by the method of rotary dispersion. J.O.S.A. & R.S.I. 7, p. 1175; 1923.

Measurements of the color temperature of the more efficient artificial light sources by the method of rotary dispersion. Sci. Papers Bur. Stand., No. 443; 1922.

Preliminary data of the color of daylight at Washington. J.O.S.A. & R.S.I. 7, p. 78; 1923.

(1) Carbon-filament lamp (4 watts per candle) giving radiation of the same composition as black-body radiation of 2077° K. By means of the system of polarizers and quartz plates this may be transformed into radiation conforming with any black-body curves for temperatures between 1800° and 2700° K.

(2) Evacuated tungsten-filament lamp, color-temperature 2360° K.; its radiation can be altered to match any radiation between 2100° and 3200° K.

(3) Gas-filled tungsten-filament lamp, color-temperature 2848° K.; all radiations between 3100° and 4200° K. can be matched.

Black-body radiation of any temperature exceeding 4200° K. cannot be matched with the sources I have just enumerated. For these cases Priest uses a slightly more complicated filter. A first quartz plate, of thickness 0.5 mm, is placed between the two polarizers, then a second plate of the same thickness beyond the second polarizer, finally a third polarizer. We then have two angles at our disposal, and hence can produce a greater variety of transmission-curves. With the gas-filled tungsten-filament lamp as source, all black-body curves for temperatures between 4200° and 24000° K. can be obtained.

Given any kind of source having approximately black-body radiation, we can produce a radiation of the same color by choosing a suitable standard source and a filter of suitable properties. The transmission-curve of the filter is known for each wave length; we know also the spectral energy-curve of the unfiltered radiation, and the visibility factor for each wave length; thence we can compute the integral transmission-factor of the filter. The results of these computations are given in a numerical table in Priest's article. These data furnish the solution for both the problem of colorimetry and the problem of photometry in so far as regards all radiations of the black-body type. In photometric work, the colors and the intensities of the radiation under study and the standard radiation are matched one after the other. In colorimetric work the matching of colors is all that needs to be done; Priest's tables give the color-temperature for every case;[20] the author has applied the method in studying some of the customary light-sources.

Priest's method is not a complete solution of the problem of heterochromatic photometry for every case, since the radiation under study must be similar to black-body radiation; still it seems competent to

[20] Priest points out that it would be more rational to define the color of a radiation by some purely optical datum, not involving a "temperature"; he suggests a wave-length which he calls the "spectral centroid." I cannot emphasize these colorimetric questions here.

render very great service. In particular, it might be made useful in calibrating the blue glasses made to modify the colors of standard radiations; this calibration would then be exempt from all heterochromatic comparisons.

Three-color method (Ives).—Ives' color-match photometer[21] offers a more nearly complete solution of the problem, for it can be applied to all kinds of light-sources in use, even those of which the radiations do not resemble black-body radiation in the least, such as the Welsbach mantle and the mercury lamp.

If we take three radiations of different colors (monochromatic or composite) and mix them in all possible proportions, we obtain a double infinity of colors, comprising *all* those lying within a certain region of the color-triangle. It is of no use to reproduce all possible colors in this manner—we require only those which may characterize customary light-sources. This obviates the necessity of using monochromatic radiations as bases, and indeed it is more advantageous, as Ives has shown, to use three composite colored radiations obtained by filtering a continuous spectrum with absorbent filters.

Ives' apparatus therefore consists of a continuous-spectrum lamp (very brilliant gas-filled tungsten lamp) and three juxtaposed colored glasses, blue, green and yellow respectively, yielding three radiations of which the spectral energy-curves are known. Each glass is bounded by a rectangular diaphragm of which the length is so adjusted that equal breadths of glass transmit luminous fluxes (of different colors) having equal luminous intensities. The luminous fluxes of the three beams can be varied independently of one another by varying the breadths of the three diaphragms. They are finally mixed with one another by a diffusing screen. Thus we can obtain a radiation identical in color with any customary radiation whatever; moreover, in the majority of cases, the energy-curve of this radiation and the one which it matches are not very dissimilar; this would not be so if he had used three monochromatic radiations as bases.

To compare two sources A and B of different colors, we have to compare first A and then B with the trichromatic source; in each comparison the colors and the intensities are simultaneously matched, the breadths of the diaphragms being adjusted for this purpose to values which are read off upon scales. These operations furnish all the data

[21] Herbert E. Ives: A color match photometer for illuminants. J.O.S.A. & R.S.I. 7, p. 243; 1923.

required to compute the ratio between the two sources, and involve nothing but homochromatic comparisons.

VII. PHYSICAL PHOTOMETRY

The term "physical photometry" is used to designate methods of making photometric measurements which dispense with the judgment by the eye, using some other radiation-sensitive apparatus than the retina. Certain advantages may be expected from such apparatus; in particular because apparatus can be devised which gives a direct measure of the intensity (e.g. by the deviation of a galvanometer) while the eye can do nothing more than discern an identity. Apparatus of this type would be of the nature of a direct-reading instrument, while visual methods are equalization-methods.

There is a rather large number of distinct types of apparatus sensitive to radiation. If they are as yet very little used in photometry, it seems to be on the following accounts:

(a) Insufficient sensitiveness (compared with that of the eye) which characterizes most of them.

(b) Requirement of very sensitive electrical measuring-apparatus, which is generally inconvenient to manipulate.

(c) Spectral sensitivity-curve differing greatly from that of the eye, and sometimes varying from one apparatus to another of the identical type.

In spite of these difficulties, interesting efforts have been made, and it is probable that physical photometers will become practical. Hence it is worth while to give a rapid outline of the status of the question.

Photometry by energy-measurement (thermometric receiver).—The thermopile and the various thermometric radiometers give an impartial measurement of the energy of the radiations they receive; when the incident radiation is monochromatic, their readings make it possible to calculate the luminous flux by means of data on the sensitivity of the eye. This is no longer true if the radiation is complex and its spectral energy-curve—in the invisible as well as in the visible region—is not exactly known. To transform a thermometric receiver into a photometric one, it is sufficient in principle to interpose a filter which attenuates the different constituents of the radiation in suitable proportions. Let K_λ represent the relative visibility-factor for the wave-length λ; the transmission-factor of the filter should be equal to K_λ multiplied by any factor C independent of wave length—CK_λ. In particular, such a filter should be absolutely opaque to invisible radiations (for which

$K=0$), above all for the infra-red rays which form an enormous part of most of the customary radiations.

The principal factors which have inhibited the use of thermometric receivers in photometry, up to the present day, are first the difficulty of making such a filter, and second the mediocre sensitiveness of the receivers. As for the filter, it is only by accident that we can find a colored screen having just the right spectral transmission-curve. However, liquids have been proposed which possess approximately satisfactory absorption-curves.[22] In spite of its theoretical imperfection, this solution is alluring on account of its extreme simplicity; further it has the great advantage of permitting the use of a receiver with large superficial area, so that there is no need of cutting down the beam of radiation by a slit—an important matter when dealing with a receiver of limited sensitiveness. Perhaps there has been too much insistence on the imperfections of this method and too little on its advantages. In my opinion, if photometry by thermometric receivers has some chance of becoming practical, it will be—at the start, at least—through the use of a suitable absorbing screen.

A theoretically more satisfactory method is as follows: disperse the radiation under study into a spectrum, reduce the intensity of each constituent by a diaphragm of suitable length, then recombine the constituents and send the recombined beam against the receiver. Unfortunately, the limitation of the beam by the slit, which is indispensable in the dispersing apparatus, reduces the usable flux to a very low value. Blondel[23] suggested an arrangement in which the usable flux is much greater. The spectroscopic apparatus is, in a sense, reversed; the thermopile is placed in the position usually occupied by the slit, while the diaphragm, its opening cut in a suitable pattern, receives the flux to be measured. It is easy to see that the effect is the same as in the previous case, but the flux which is used is that falling upon a large surface, not merely a slit. The first results obtained are encouraging.

To summarize: we may hope that a good direct-reading method of photometry will eventually be developed from the use of the thermometric receiver. One of the first problems to be solved is the construction of a receiver (thermopile with galvanometer, or any other radi-

[22] See the report of the American National Committee on Illumination: Latest progress in physical photometry. Commission internationale de l'éclairage, Paris convention, 1921.

[23] Sur une solution de la photométrie hétérochrome permettant une mesure physique de l'intensité lumineuse d'un rayonnement. C. R. *169*, p. 930; 1919.

ometric system) sufficiently sensitive and sufficiently robust. The question seems important enough to induce some apparatus-maker to devote his efforts to it.

Use of selenium and similar substances.—The electrical resistance of these substances diminishes when a luminous flux falls upon any of them. The methods in which this effect is utilized involve apparatus which is fairly simple and fairly sensitive. Unfortunately the properties of selenium (the earliest-known of these substances) are complicated by many features (hysteresis, selective sensitiveness differing from one sample to another, effect not proportional to intensity of radiation) by which its behavior seems to be made unreliable. Within the last few years, artificial substances with similar properties have been developed; Case is said to have built an apparatus of which the spectral sensitivity-curve is practically identical with that of the eye. If this is confirmed, the apparatus can be applied in practice.

Photoelectric cells.—These instruments, in which the emission of negative charge is provoked by radiation, may become receivers of great sensitiveness. Unfortunately, their spectral sensitivity-curves differ greatly from one cell to another. Interesting applications of these instruments in astronomical photometry and in spectrophotometry have already been made; but these are applications in which, if necessary, it is permissible to pay little attention to the variation of sensitiveness with wavelength. Apparently there has been no application to practical photometry.

Use of the photographic plate.—As a receiving apparatus for radiation, the photographic plate has valuable qualities. Generally employed to record the shapes and positions of images, it can also, though not so easily, be used to measure intensities by virtue of the degree of blackening produced under given conditions. However, ordinary photographic plates have spectral sensitivity-curves differing very much from that of the eye, and the results they present in heterochromatic comparisons are very different from those obtained by visual photometry. By suitable processes (ortho-chromatism) the sensitiveness of a plate can now be extended to cover the whole visible spectrum; and, by interposing a well-selected filter, it is possible to obtain a sensitivity-curve much like that of the eye. The astronomers who have used the photographic plate in this way have given the name "photovisual methods" to determinations made thus, and have found them to agree well with direct visual measurements.

Photographic photometry has this in common with visual measurements, that it always involves comparisons, never a direct reading. The analysis of the photographs (involving photometric measurements of the "density" of the plates) is rather tedious; on the other hand, a great number of 'documents' can be gathered together in a short time, and examined at leisure in one's laboratory. Apart from its frequent use in astronomy, interesting practical applications of the photographic plate have already been made.[24] It would be worth while to undertake a systematic study of the photographic method.

VIII. CONCLUSION

Heterochromatic photometry has long been regarded as being purely a problem of physiological optics, in which every individual case involved all the difficulties of the general problem, and had to be treated independently of all previous research. Some observers, following Abney, declared that heterochromatic comparisons are almost as easy and exact as homochromatic ones; but the majority realized, with every new experiment, the difficulty and the uncertainty of the measurements. During this period the study of the energetics of radiation, which was only beginning to become exact, contributed nothing to the solution of the photometric problem

In the last few years the question has undergone a complete change in aspect. In several quarters the idea has arisen that it is exceedingly important to eliminate all heterochromatic measurements from ordinary practical work, by devising methods in which such measurements are performed and the delicate questions they involve settled once for all at the beginning. We can already discern the approaching period when heterochromatic photometry will become solely a question for the research laboratory, and routine practice will be entirely freed of it, the practical measurements being made as homochromatic comparisons, or else without the use of the eye in any way.

The data about the eye, and particularly the curve of relative visibility, are beginning to be pretty well known. There will always be something arbitrary about them, owing to the differences between individuals and to the question of defining the "normal" eye; it will be necessary to *define* the values of relative luminosity by a numerical table representing the results of experiment as well as possible.

[24] See in particular: Ives and Luckiesh: The distribution of luminosity in nature. Trans. Illum. Eng. Soc. *6*, 687 (1911). A photographie method for recording candle-power distribution curves. Elec. World *60*, p. 153; 1912.

As for the purely physical data, there is no uncertainty about defining them; we can hope only for an increased precision in the determinations. These data are of two kinds: those concerning the instruments used, and those relating to the energetics of the radiations which have to be studied. As for the instruments, we should demand above all exact information about such of their properties as vary with the wavelength of the radiation. No absorbing filter, colored or neutral, should be used unless its spectral transmission-curve is exactly known. For this reason the spectrophotometer, of which satisfactory models already exist, becomes especially important. As for the energy-curves of the various sorts of radiation, the most salient feature of the latest researches probably is the increasing emphasis laid upon the "black-body" type. This new orientation corresponds, it is true, to a restriction of the problem of heterochromatic photometry. The perfectly general problem accepted in the heroic age of heterochromatic photometry, and which in those days the observers tried to solve directly in each case, has been in a sense abandoned; but the restricted problem, confined to radiations of continuous spectra analogous to the black-body spectrum, includes the really important practical cases; and, since this problem can be solved exactly and simply, we may hope that the study of it will lead to great advances. The constitution of such radiations is defined by a single variable, which may be the "temperature" parameter occurring in the Planck formula, or any other parameter defining the energy-curve in the visible spectrum; the color of the radiation is defined in the same way. The questions of photometry are thus connected with the problem of optical pyrometry and the problem of colorimetry; these three techniques have been of mutual assistance in forwarding the progress, each of the others, in the last few years.

Colored filters might be made more broadly useful and more reliable than they are today; but it is not enough to regard them as "monochromatic." A complete knowledge of their absorbing properties, and studies of the constancy of absorption by different liquids, would be valuable in furthering progress in the use of colored absorbents.[25]

It is to be hoped that physicists will not lose interest in the problems of pure physics which must be studied in order to attain a practical and definitive solution of the problem of heterochromatic photometry.

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[25] The Committee on Heterochromatic Photometry was instructed at the Geneva meeting to consider the question of color filters.

Atom-Lattice of Argon.—Solid argon, the first element in the inert-gas column of the periodic table to have its atom-lattice determined, displays a face-centered cubic lattice with spacing 5.42 ± 0.02A, and least distance between centers of adjacent atoms 3.84A. We note that although it is supposed that the inertness of argon is due to its having 8 symmetrically arranged outer electrons, the argon atoms in this lattice have not 8 but 12 nearest neighbors. In solid KCl, which is composed of atoms having the same number of electrons (although not the same nuclear charges) as argon atoms, the least distance between centers of adjacent atoms is 3.12. (I may add that the radius of the free argon atom with respect to collisions with others, as determined from the viscosity of gaseous A, is 1.4A.) Born has shown that if the atoms in a regularly crystallizing solid attract one another with a force varying inversely as the mth, and repel one another with a force varying inversely as the nth, power of the distance; then the product of m and n can be calculated from the compressibility, atomic volume, and heat of sublimation of the solid. Only the last two quantities are known for argon, but the authors guess the first from the density and specific heat, and find $mn = 135$. There is some reason for supposing that we should so subdivide this product as to make $m = 5$ and $n = 15$, although for metals the value 3 is generally assigned to m. [F. Simon and C. v. Simson, Berlin; ZS. f. Phys. *25*, pp. 160-164; 1924.]

KARL K. DARROW

Critical Temperature for Condensation of Cadmium Vapor upon Paraffin and Mica.—The apparatus consisted essentially of a strip of copper covered with paraffin or mica, heated by an electric oven at one end and cooled to liquid air temperature at the other, so as to establish a temperature gradient along it; and parallel to it a wire coated with cadmium. These were enclosed in an evacuated tube immersed in liquid air. When some of the cadmium was driven off from the wire by sending a heating current through it, a visible film appeared on the cooler part of the strip, sharply bounded (in the best behaved experiments) towards the hotter end; pretty photographs of the boundary are shown. The temperature at the boundary, which is the critical temperature of condensation, was estimated (by interpolation between the readings of 3 thermocouples fixed to the strip at three points along its length) at 203° to 206° K for paraffin and 193° to 196° K for mica. Test experiments in which longitudinal halves of the strip are covered one with paraffin and the other with mica show that the critical temperatures for the two are distinct. [J. Chariton and N. Semenoff, St. Petersburg; ZS. f. Phys. *25*, pp. 287-291; 1924.]

KARL K. DARROW

PHYSICAL OPTICS

REPORT OF O. S. A. PROGRESS COMMITTEE* FOR 1923-4

The past period of a year or more has been one of great activity in Physical Optics. While it is not easy to define sharply the limits of this field—because the electron sometimes refuses to indicate which of its various activities are to be classified as *light* and which heat, or electricity and magnetism—it includes, even in its narrowest sense, many hundreds of titles and it is obviously impossible to mention more than a fraction of these in a brief report. In some cases only the general trend of research can be indicated. For the sake of clearness the matter is grouped in a number of sub-titles.

EMISSION: ATOMIC THEORY

New Series and Series Classification. Up to 1922 practically all our knowledge of spectral relationships was limited to the elements H, He and those in the first three columns of the periodic table. Since that time wonderful progress has been made, and it is justifiable to expect almost complete classification of line spectra within a very few years. Even the very complicated spectra, such as those of Fe, Mn, Ti, etc., have yielded to the new methods of analysis. About a quarter of the iron lines are now classified, and Russell is about to publish a practically complete analysis of the titanium spectrum.

The chief reasons for this advance in spectral series classification are the application of (1) Sommerfeld's[1] intensity rule, according to which the strongest lines are those in which the azimuthal and inner quantum numbers change in the same sense, (2) Landé's[2] structure and interval rules for multiplets, and (3) Landé's[2] theory of the Zeeman effect. With these aids, the structure of a multiplet may be worked out as soon as a few of its components have been identified (by their Zeeman patterns, behavior under different physical conditions) and as soon as the structure is known the spectral nature of the terms is known and the search for other related lines is facilitated.

* The Progress Committee on Physical Optics for 1923-4 consists of the following members: K. T. Compton, Princeton University; L. R. Ingersoll, University of Wisconsin, Chairman; E. P. Lewis, University of California; W. F. Meggers, Bureau of Standards; and H. M. Reese, University of Missouri.

[1] Atombau, 3rd Ed., p. 447.

[2] Zs. f. Phys. *11*, p. 353, 1922; *15*, p. 189, 1923; *19*, p. 112, 1923.

Important supplementary evidence is afforded by the temperature classification of the lines. Their intensities in stars of various temperatures or in the electric furnace, considered in the light of theories of thermal equilibrium advanced by Saha[3] and others, serve to identify them as spark or arc lines and give indication of their nature as principal or subordinate series lines. It may be remarked that in a forthcoming contribution from the Mt. Wilson Solar Observatory, by Russell, there will be listed the 200 most important lines of at least 43 different elements, giving their spectroscopic character, excitation potential and the ionizing potential of the element.

Displacement Law. Much attention has been devoted to the Kossel-Sommerfeld Displacement Law, which asserts that the loss of each electron by an atom displaces it one column to the left in the periodic table, in respect to the character of its spectrum. The law affords a striking confirmation of modern views of atomic structure and the interpretation of the periodic table. A forthcoming paper from the Bureau of Standards will review some new evidence for this law.

Critical Energies. Excitation Function. Considerable attention has been devoted to the direct measurement of energy differences between atoms in their various states, as well as to a study of the conditions of excitation which determine the intensities of spectral lines. The subject of critical energies is exhaustively treated in a Bulletin of the National Research Council by Compton and Mohler, just published. It may be remarked that methods have been so improved and so extensively used that a great mass of useful data has been collected for those substances which can be worked with in the gaseous or vapor conditions.

The other aspect of the problem, the study of intensities, has for its prime object the discovery of laws regarding the mechanism of radiation. The quantum theory of stationary atomic states gives frequency relationships, but throws no light on the actual process of light emission by an atom—except that the entire atom or molecule and not the radiating electron alone, is involved in the process. As a first step in this investigation, attempts have been made to study quantitatively the probabilities of transfer from one excited state to another, and the physical conditions which affect these probabilities. For example, a mercury atom in the 3S state may revert to the $2P$ state, emitting 4916A, or to the $2p_2$ state, emitting 2857A. The relative intensities

[3] Phil. Mag. *40*, pp. 472, 809; 1920.

of these lines give a measure of the relative probabilities of making one or the other quantum jump. These probabilities may be spontaneous, but more likely are governed by the radiation field in which the atom is placed. Similarly, relative intensities of absorption lines due to transitions from the same atomic state give probabilities of transitions induced by radiation of different frequencies. This study involves the difficult technique of accurate quantitative measurements of light intensity, and is still in its infancy. Perhaps great progress may come along these lines; certain it is that none of our knowledge of series relationships and atomic structure could have been gained if wave length determinations had been no more accurate than intensity measurements are at the present time.

Hughes and his collaborators[4] have begun a systematic study of relative intensities of spectral lines excited by electron impacts, as a function of the energy of these impacts, keeping all other conditions as nearly constant as possible.

R. W. Wood is carrying on some intensely interesting and striking experiments on effects of small traces of impurities on relative intensities. For instance, the admixture of a little nitrogen and a bare trace of water vapor causes the intensity of the mercury line 2967A to increase thirty-fold. The cause of this is still obscure, but must have an intimate bearing on the actual mechanism of radiation. An account of these experiments will soon appear in the Proceedings of the Royal Society.

STANDARD WAVE LENGTHS

The International Astronomical Union[5] in 1922, adopted a system of 20 neon lines (5852.488 − 7032.412A) as secondary standards, and 302 tertiary standards from the spectrum of the iron arc (3370.789 − 6750.163A). The latter were based upon the best values of iron lines interpolated between 80 secondary standards previously adopted by the International Union for Cooperation in Solar Research.

The Committee dealing with this subject for the International Astronomical Union made a number of recommendations relative to secondary standards, and among these the new specifications for the iron arc are perhaps the most important, since the changes in this source have led to several redeterminations of the secondary standards. Results of the first[6] of these more recent investigations were published

[4] Hughes and Lowe, Phys. Rev. *21*, p. 292, 1923; Proc. Roy. Soc. A, *104*, p. 480, 1923.
[5] Transactions, International Astronomical Union, *1*, p. 35, 1922.
[6] Meggers, Kiess and Burns, Sci. Papers, Bur. Stds. *19*, p. 263, 1924.

in 1924 by the Bureau of Standards. For wave lengths shorter than 4000 A, the new results are in fair agreement with the internationally adopted values, but for longer waves the new values are systematically and progressively smaller than the secondary standards, the difference amounting to about 1 part in 1,000,000 in the red. In making the new measurements, wave lengths from the iron arc were, for the first time, compared directly with the wave length of the red radiation from cadmium as emitted by a lamp of the same type as that used in the measurement of the international meter. Although no details are as yet available, similar results[7] have been obtained at the Mt. Wilson Observatory according to a published statement that new preliminary values found for a selected list of lines in the red and green are on the average 0.008 A and 0.003 A smaller respectively than the adopted values in these spectral regions. The true causes for the observed differences are not definitely known. Another contribution[8] to the subject has lately been made at the University of Bonn where the values of 30 iron lines (3558.520-5341.027 A) 32 neon lines (5852.488–7544.053 A) and 8 cadmium lines (3466.200–5085.823A) have been measured relative to the red line of cadmium from a quartz cadmium-arc lamp. Substantial agreement with the adopted values for iron and neon lines was found, but it is perhaps doubtful if these results may be compared with those of the Bureau of Standards since different types of cadmium and neon sources were used in the two laboratories.

It appears that if the highest possible precision of wave length standards is to be attained, it will be necessary to define the sources, their operation, and the method of observing in more detail than heretofore.

A development of great importance to the subject of secondary standards is the discovery[9] of regularities in the spectrum of the iron arc. Critical tests[10] of the accuracy in relative values of such standards have been made from (1) the recurrence of differences of wave-number which should be exactly the same in all multiplets involving one set of spectral terms in common, and from (2) cyclical relations of multiplets in groups of four such that the wave-numbers for any one of them may be calculated from those of the other three. These tests show that

[7] Babcock, Phys. Rev. *24*, p. 205, 1924.
[8] Wallerath, Ann. der Phys., *75*, p. 37, 1924.
[9] Walters, Jour. Wash. Acad. Sci., *13*, p. 243; 1923; J.O.S.A. and R.S. I., 8, p. 245, 1924.
[10] Meggers, Astrophys. Journ., *60*, p. 60, 1924.

most of the standards appearing in any one multiplet are correct in relative value to one part in two or three millions, but errors ten times larger may exist for lines in the infrared or in the ultraviolet. It has been suggested that the effects of pressure and the so-called pole effects can be eliminated, and the accuracy of standard wave lengths increased by the adoption of the iron arc in vacuo as a source.

In addition to the results mentioned above, attention should be called to two sets of interferometer measurements of wave lengths made for the purpose of extending the system of secondary standards to shorter and to longer waves. Ten lines (2112.105-2369.891 A) of the copper-tin ultraviolet spectrum were measured[11] in the laboratory of Professor Fabry at the University of Paris, and 75 iron-arc lines (6750.157-8824.238 A) were measured[12] in the red and infrared at the Bureau of Standards.

The recognized value of titanium as a comparison spectrum led to a determination of the wave lengths of 118 titanium lines (4250.794-6261.097 A) by means of the interferometer. This investigation[13] was carried out at the Northwestern University with vacuum arcs of cadmium and titanium. Interferometer measurements of the vacuum-arc wave lengths of 25 iron lines, two manganese lines, and three cadmium lines were also included.

A comprehensive cooperative program of work on solar-spectrum standards of wave length was begun in 1923 by the Allegheny Observatory and the Bureau of Standards. Some preliminary results[14] of a comparison of solar wave lengths and neon standards have already been reported.

GENERAL SPECTROSCOPY

Ultraviolet. In the extreme ultraviolet great progress has been made by a number of investigators. Hopfield[15] has extended the known members of the Lyman series of hydrogen to the sixth member. He observed the oxygen vacuum tube spectrum through and beyond the absorption band, and discovered new triplets in the spectra of oxygen and sulphur. He has also investigated the spectrum of chlorine to 790 A. Simeon[16] has discovered new lines of carbon in arc and spark

[11] Mitra Annales de Phys., *19*, p. 315, 1923.
[12] Meggers and Kiess, Sci. Papers, Bur. Stds., *19*, p. 273; 1924.
[13] Brown, Astrophys. Journ., *56*, p. 53; 1922.
[14] National Academy of Sciences, April Meeting, 1924.
[15] Nature, *110*, p. 732, 1923; *112*, p. 437, 1923; Astrophys. Jour., *59*, p. 114, 1924; Phys Rev., *23*, p. 766, 1924.
[16] Proc. Roy. Soc., *102*, p. 484, 1923; *104*, p. 368, 1923.

spectra of Cd, Zn, and C down to 595 A. Millikan and Bowen[17] have investigated the hot spark spectra of twenty elements from H to Cu, the shortest wave length obtained being that of oxygen at 136.6 A. Many lines associated with x-ray levels have been obtained, principally from the *L* and *M* levels and many series lines due to multiply ionized atoms have been found. From the constants of the *L* and *M* levels the screening constants are determined. The strongest lines are generally emitted by *stripped* atoms, i.e., those which have lost their valence electrons by ionization. This method seems best for connecting optical and x-ray spectra. Lyman[18] has investigated the spectrum of helium with several gratings. He confirms the existence of the second enhanced series, and has discovered two members of a new enhanced series at 703 A and 256 A. A new principal series of seven members, with the first line at 584 A, was also found. Both Millikan and Lyman find that work in this region is facilitated by the use of gratings ruled very lightly.

Hafnium. The existence of a new element has been confirmed by optical and x-ray spectroscopy. There was a gap in the series of atomic numbers which according to the Bohr theory should correspond to an element of the zircon group. Coster and Hevesy[19] discovered this element in a systematic x-ray analysis of zircon minerals, in which it occurs in considerable quantities. They called it hafnium, and its atomic weight is approximately 180. The optical spectrum has been studied by Hansen and Werner.[20]

Compton Effect. Judging from reports at the Toronto meeting of the British Association, the Compton effect—that is, the shift in wave length of scattered x-rays—continues to gain adherents. Duane still fails to find this effect but does, however, note a curious shift in the same sense and of similar magnitude when the x-ray tube is surrounded by a wooden box. Whether or not there is a connection between the two effects remains to be seen, but it is evident that this new and curious "box effect" must receive further investigation.

Einstein Shift. The question of the Einstein shift of solar lines remains unsettled. Croze[21] finds that observed shifts are not proportional to wave length, vary with the intensity, and vary from one element to the other. He concludes that the shifts are due to other causes.

[17] Phys. Rev., *23*, p. 1, 1924.
[18] Astrophys. Jour., *60*, p. 1, 1924.
[19] Nature, *111*, Jan. 20, Feb. 10, Feb. 24, 1923.
[20] Nature, *112*, p. 618; 1923.
[21] Ann. de Phys., *19*, p. 93, 1923.

St. John[22] concludes that the effects of pressure in the reversing layer of the sun are negligible in producing shifts, and that after the effects of radial motion, and scattering have been eliminated there remain differences between solar and laboratory wave lengths of the order called for by the Einstein theory.

H. D. Curtis[23] reports on the work of Burns and Meggers with a combination of grating and interferometer capable of detecting one-tenth of the Einstein shift. All shifts of the lines measured are in the proper direction, but are very small for faint lines and much greater than the Einstein shift for intense lines. He concludes that the Einstein theory is disproved.

Infrared. An important addition to our knowledge of the spectrum of hydrogen has been made by Brackett[24] who discovered the first two members of an infrared series due to electrons falling into the fourth energy level, with wave lengths 4.05 μ and 2.6 μ. He also found three additional members of the Paschen series.

Pfund[25] finds an emission maximum for hydrogen at 7.40 μ which is apparently the first line in another new series (*O* series). The calculated wave length is 7.46 μ.

The infrared spectra of zinc and cadmium have been studied between 1μ and 5μ by Randall and St. Peter.[26] They used a grating of the echellette type, with 7300 lines to the inch, ruled for maximum energy in the neighborhood of 2.5 μ. The results demonstrate the effectiveness of this type of grating for infrared work.

Shortest Hertzian Waves. The spectrum gap which has hitherto existed between the longest infrared and the shortest Hertzian waves has finally been closed—with some overlapping. Rubens found wave lengths in the mercury arc as long as .32 mm, while Hertzian waves down to 3 mm in length have been previously produced. The closing of this gap has proved exceedingly difficult because of the very minute oscillators necessary to give these short waves. Nichols and Tear[27] using electrodes only .1 mm in diameter and .1 mm long, with glass seals so skillfully made that they covered only half the length (!) have succeeded in generating fundamental wave lengths of the order of

[22] Science, *58*, p. 334, 1923.
[23] Science *59*, p. 443, 1924.
[24] Astrophys. Jour. *56*, p. 154, 1922.
[25] J.O.S.A. and R.S.I., *9*, p. 193, 1924.
[26] Phys. Rev., *23*, p. 766, 1924.
[27] E. F. Nichols and J. D. Tear, Phys. Rev., *21*, p. 587, 1923.

1 mm. These have been measured with a type of echelon and a special radiometer arrangement. In addition to these fundamental waves, moreover, the interference curves also showed the presence of harmonics which have been found as short as .22 of a mm.

The most recent work reported is that of Glagolewa-Arkadiewa[28] in Moscow, who used a peculiar type of oscillator consisting of a mass of stirred metal filings of fairly uniform size. The analysis of this radiation gives clear indication of waves down to .2 mm length or even somewhat shorter.

OTHER OPTICAL EFFECTS

Resonance and Fluorescence. The resonance spectrum of iodine in the extreme ultraviolet has been studied by Oldenberg.[29] Series of lines similar to those described by Wood were excited by the light of sparks. When excited by the line λ 1900 A of tin there were five resonance lines of shorter and 35 of greater wave length. Beyond these came the complete band spectrum, which was not observed in Wood's experiments. This is difficult to reconcile with theories of band excitation.

E. L. Nichols and Howes[30] find that resonance and fluorescence effects are excited by light from various sources in passing through an air-hydrogen blast flame colored with vapors of Li, Na, Ca, Sr, Ba, Th, etc. Lines and bands are increased in intensity and the green thallium line is greatly enhanced by light of its own wave length and other thallium lines, but not by radiations from the mercury arc, showing that the luminescence is selective.

Polarization of Resonance Radiation. Wood and Ellett[31] have amplified and extended their work on the effect of a weak magnetic field on the polarization of resonance radiation of mercury and sodium. They find that a field of no more than 2 gauss is sufficient to cause the remarkable changes in polarization reported by them a year ago. Breit[32] and also Eldridge[33] have worked out quantitative explanations of these phenomena—based on the Zeeman effect and making use of the Larmor precession—which, on the whole, fit the facts reasonably well.

[28] Zeit. f. Phys. *24*, p. 153, 1924.
[29] Zeit. f. Phys., *18*, p. 1, 1923.
[30] Phys Rev., *22*, 425, 1923; *23*, 472, 1924.
[31] Phys. Rev., *24*, 243, 1924.
[32] Phil. Mag. *47*, p. 832, 1924.
[33] Phys. Rev. *24*, p. 234, 1924.

Polarization of Scattered Light. Lord Rayleigh and others have shown that the light scattered transversely by gases is not in general perfectly polarized, but shows a certain defect of polarization characteristic of each gas. This has been explained by assuming an optical anisotropy of the scattering molecules which is greater the more complex the molecule. The subject has been treated both theoretically and experimentally by Raman and Rav[34], L. V. King,[35] J. C. K. Rav,[36] Raman and Ramanthan[37], Cabannes and Granier[38] and others.

Zeeman Effect. Babcock[39] at Mt. Wilson has carried out a large series of measurements of the Zeeman effect, from which 49 separate values of the ratio e/m have been derived. About 40 lines in the blue region of the chromium spectrum were most frequently used and these were supplemented by 76 other lines of chromium, titanium, zinc, and barium. The field strengths used averaged 30,000 gauss. The final result is $e/m = 1.761 \times 10^7$, with a probable error of 1 part in 1800.

Absorption. The absorption spectrum of lithium vapor has been obtained by Narayan and Gunnaiya[40] and bands similar to those of sodium and potassium found, as well as lines of the principal series. One group extends to each side of the red line, and there is another in the blue-green region.

The absorption spectra of sodium, potassium, and other monatomic metallic vapors at moderate temperatures contain not only lines, but bands, characteristic of the molecular state. These bands, as well as those found in the emission spectra of such monatomic elements as helium and mercury under certain conditions, are supposed to be due to metastable molecular compounds formed by atoms "excited" by light or electrical stimulus by the removal of an electron from its normal energy level. Barratt[41] obtained direct evidence of the formation of molecular compounds between atoms of different metals by finding a new band absorption spectrum between the limits 5955 A and 5646 A in a mixture of sodium and potassium vapors, presumably due to the combination NaK.

Interference. With the aid of microphotographs using polarized

[34] Phil. Mag. *46*, p. 426, 1923.
[35] Roy. Soc. Proc. *104*, p. 333, 1923.
[36] Phys. Rev. *22*, p. 78, 1923.
[37] Roy Soc. Proc., *104*, p. 357, 1923.
[38] J. d. Phys. et le Radium, *4*, p. 429, 1923.
[39] Astrophy. J., *58*, p. 149, 1923.
[40] Proc. Roy. Soc., *106*, p. 51, 1924
[41] Proc. Roy. Soc., *105*, p. 221, 1923.

light Lord Rayleigh[42] has been able to explain the colors of crystals, shells, and beetles. Some crystals of potassium chlorate show a complex structure composed of periodic groups of uniformly spaced twin planes at relatively great distances from each other. The high order of interference gives complex reflection spectra. In shells the colors are produced in two ways, in agreement with the views of Brewster and Pfund. The transferable colors (capable of transfer to soft wax by pressure) are due to the outcropping edges of equally spaced layers; the non-transferable colors are due to reflection from successive layers, as in the case of Lippman films.

The colors of feathers have been studied by Mason,[43] with the aid of the microscope and polarized light, and by immersion in media of different refractive index. He found that the non-iridescent blues are due to the scattering of blue light by fine pores in the cell walls of the feather. Green is due to essentially the same structure, the effect being modified by transparent yellow layers covering the blue cells. The iridescent colors are due to interference in thin laminae or films. In no case was any indication of pigment colors or metallic reflection found.

Dispersion in Interstellar Space. The question as to whether different colors of light have exactly the same velocity in free space seems finally to have been settled. It may be remembered that nearly two decades ago Nordmann[44] and Tikhoff[45] brought forth independent and somewhat disconcerting evidence indicating the presence of something corresponding to dispersion in free space. Their results, however, showed great disagreement. Shapley[46] has made exposures at Mount Wilson with yellow and blue light on a cluster of variable stars some 40,000 light years distant. The result is a possible difference of not more than a minute for the time required to traverse this distance, or in other words, the velocities for the yellow and blue cannot differ by more than one part in 20,000,000,000.

PHOTOELECTRIC EFFECT

Vapors. Referring briefly to the photoelectric effect, this phenomenon has now been found in metallic vapors. Williamson[47] finds for potassium

[42] Proc. Roy. Soc., *102*, p. 668, 1923; *103*, p. 34, 1923; *103*, p. 233, 1923.
[43] J. Phys. Chem., *27*, pp. 201, 401; 1923.
[44] C. R. *146*, p. 266, 383; 1908.
[45] C. R., *146*, p. 570, 1908.
[46] Nat. Acad. Sci. Proc., *9*, p. 386, 1923.
[47] Phys. Rev. *21*, p. 107, 1923.

vapor a long wave limit of about 2800 A which is in reasonable agreement with the wave length computed on the basis of the quantum theory from the ionizing potential. Kunz and Williams[48] find for caesium vapor a long wave limit of 3180 A, while the limit of the principal series, according to Fowler, is 3184 A.

Electron Velocities. There has been some interest in the question of the velocities of emitted electrons from the two sides of a thin film. Piersol[49] finds the two velocities to be the same and believes that the contrary conclusion reached by former workers was probably caused by stray light of shorter wave lengths than that under examination. Chien Cha, in a paper read at the Cincinnati meeting of the Physical Society in December, 1923, reported that he finds a difference of about 20% between the velocities on the incident and emergent sides for cathodically deposited films, but none for films produced by evaporation.

Temperature Effect. In the matter of temperature effect, Ives[50] working with highly exhausted cells of various forms, finds that the photo-electric current decreases very considerably as the temperature is lowered to -180^{c} C. He is convinced that the phenomenon is not a spurious effect caused by change in gas pressure or absorption of gas, but is an actual change in the work function of the metal directly due to change in temperature. Burt, however, in a paper at the Stanford meeting of the American Physical Society in June, finds no such change in special electrolytically prepared sodium.

QUANTUM AND WAVE THEORY

In concluding this discussion of progress in physical optics we must mention one field in which the advance has been slow: this is in the reconciliation of the quantum and wave theories. Lorentz[51] in reviewing the situation refers to this difficulty as a heavy cloud over this part of physics. The concentrated quanta which the photo-electric effect seems to demand are hard to reconcile with the widely extended quanta which apparently would have to be assumed if we were to explain on this basis interference and diffraction effects, such, for instance, as Michelson's measurement of star diameters.

A great deal of attention is being devoted to this problem, however,—

[48] Phys. Rev., *22*, p. 456, 1923.
[49] Phys. Rev., *23*, p. 144; 1924.
[50] J.O.S.A. and R.S.I., *8*, p. 551; 1924.
[51] Nature, *113*, p. 608; 1924.

witness recent papers by Duane,[52] Darwin,[53] Epstein and Ehrenfest,[54] Bohr, Kramers and Slater,[55] and others—and there are doubtless many who would disagree with the statement that we are not making satisfactory progress in the solution.

Duane's point of view is interesting. From dimensional reasoning he is led to assume that the components of momentum of radiation transferred to matter upon which it is incident are integral multiples of h/l, where l is a length characteristic of the matter and extending in the given direction. By the application of this principle all interference phenomena, including the newly discovered reflection of x-rays characteristic of the chemical elements of the reflecting crystal, can be explained. A. H. Compton[56] has recently shown that Duane's assumption may be included in a generalized interpretation of the quantum integral.

Bohr, Kramers and Slater[55] point out a possible way of reconciling the essentially discontinuous nature of quantum phenomena with the continuous action required by classical electromagnetic theory. The essential concept is that every atom, in addition to its properties as defined by the quantum theory, is a "virtual oscillator," continually giving out all types of radiation which it could possibly radiate by transitions to other stationary states. Thus every atom is in radiation communication with every other by this "virtual field of radiation." The effectiveness of this "virtual radiation" is that it creates a probability that any atom in its field will change its quantum state. Any such *spontaneous* changes are due to and determined by the virtual radiation field of the same atom, while *induced* changes are determined by the virtual radiation field from other atoms. Ordinary classical laws apply to this "virtual radiation," except that principles of conservation of energy and momentum are considered to be simply average or probability effects. It is shown that this point of view is consistent with the correspondence principle, and it is used to interpret a number of phenomena. While at first glance the theory seems vague and unreal, perhaps further thought along these unaccustomed lines will lead to a better understanding of its significance and possibilities.

OCT. 15, 1924.

[52] Nat. Acad. Sci. Proc., *9*, p. 158, 1923.
[53] Ibid, *9*, p. 25, 1923.
[54] Ibid, *10*, p. 133, 1924.
[55] Phil. Mag., *47*, p. 785, 1924.
[56] Phys. Rev., *23*, p. 118, 1924.

INSTRUMENT SECTION

A NEW METHOD FOR PHOTOGRAPHIC SPECTROPHOTOMETRY*

By Loyd A. Jones

The photographic plate has been used for many years in spectrophotometric work and owing to its sensibility to radiation of frequencies outside of the visible spectrum, has become practically indispensible where it is necessary to work in regions of low or complete invisibility. Since there are many possibilities of error inherent in the use of the photographic plate for obtaining precise quantitative measurements of intensity, many workers have preferred to use visual methods whenever possible and the photographic plate has not come into general use for spectrophotometric work in the visible region.

The photographic method has many advantages to recommend its adoption, even for work in the visible region. Long continued spectrophotometric observation is notorious in the production of excessive visual fatigue and the avoidance of this is obviously desirable. The possibility of obtaining a complete spectrophotometric record throughout a relatively wide range of wave lengths in a very short time and the production of a permanent and authentic record which may be preserved for reference, are factors which may be of great value in many instances. These virtues become of sufficient consequence to warrant the adoption of this method however, only on the condition that a degree of precision equal to, or greater than that obtained visually, can be secured. Unfortunately many methods of using the photographic plate for this type of work have been devised without complete knowledge or due consideration of the inherent characteristics of these materials, with the consequence that the results obtained have been more or less disappointing from the standpoint of precision and repeatability. Failures to obtain the required precision, which are usually traceable to improper usage or lack of knowledge of the fundamental characteristics of photographic materials, should not be considered as sufficient evidence for unqualified condemnation. The author feels very strongly that with a proper experimental technique and intelligent

* Communication No. 221 from the Research Laboratory of the Eastman Kodak Co.

interpretation of the results, the photographic method is capable of giving spectrophotometric data equal or superior to that obtained visually.

The foregoing remarks should not be interpreted as intending to convey the impression that no satisfactory methods have been developed, for such is not the case. Some very good instruments have been devised and results of satisfactory quality are being obtained by their use. The literature of photographic spectrophotometry is very voluminous and no attempt will be made at this time to review the work that has been done in this field or to present a bibliography of the subject. The method to be described in the following pages involves some new features and, while not free from all possible objections, has been designed specifically to eliminate all errors arising from the peculiar characteristics of photographic materials.

It may be advisable before proceeding further with the discussion, to state briefly some of the peculiarities of photographic materials which may give rise to errors when these materials are used for the measurement of radiation intensities.

Intermittency effect. A photographic plate does not in general integrate correctly an intermittent exposure. An exposure (Exposure, E = Intensity, $I \times$ Time, t) of definite magnitude given as a series of intermittent flashes generally yields, upon development, a lesser density than the same exposure applied continuously. Hence only under certain conditions will correct values of intensity be obtained if the exposing mechanism is of the intermittent type.

Failure of the reciprocity law. The density produced by a given exposure E is dependent not only upon the value of exposure $E = I \cdot t$ but upon the magnitudes of intensity, I and exposure time, t.

Gamma-wave length effect. The contrast (gamma, γ) produced in a fixed time of development is dependent upon the wave length of the exposing radiation and may vary to a great extent for a relatively small difference in wave length.

Nonuniformity of effective sensitivity. The most carefully made photographic materials may show measurable differences in sensitivity at various points, even when the area used is relatively small. These variations in effective sensitivity may be due to such factors as inequality in the thickness of coating, variation in the specific sensitivity of the emulsion or slight differences in the rate at which development takes place at different points on the plate. While these inequalities are in general too small to be of consequence in the practical work to

which these materials are usually applied they may become of great importance and of sufficient magnitude to introduce serious errors when an attempt is made to use these materials for the purposes of quantitative scientific measurement.

Errors of development. It is very difficult to develop two samples of photographic material to exactly the same extent. This is due to many factors such as the variation in the rate of circulation of the developing solution over the surface of the plates or films, variation in temperature and time of development, etc. It is inadvisable and unnecessary for the purpose of this paper to discuss these factors in detail.

From a consideration of these characteristics the conditions under which two radiation intensities are equal may be rigidly specified. Let two immediately adjacent small areas, A and B, on the surface of a photographic material be exposed to the two intensities to be compared. Let this exposed material be developed in such a way that the two areas receive precisely the same treatment in developing, fixing, washing, drying, etc., and the resultant density be measured under identical conditions of illumination and observation. Let the various factors involved be designated for convenience as follows:

Area	A	B
Intensity of incident radiation	I_1	I_2
Wave length of incident radiation	λ_1	λ_2
Exposure time	t_1	t_2
Density	D_1	D_2

In general I_1 is equal to I_2 only when both exposures were made non-intermittently and when

$$t_1 = t_2 ,$$

$$\lambda_1 = \lambda_2 , \text{ and}$$

$$D_1 = D_2$$

The method proposed meets the above requirements and the precision obtainable should be limited only by the exactness with which the mechanical and optical requirements can be met and by the error involved in the determination of density equality ($D_1 = D_2$).

The principle involved can best be explained by aid of graphic illustration and for this purpose reference is made to Fig. No. 1.

On the photographic plate P let a narrow rectangular area A be subjected to an exposure increasing logarithmically from right to left. The distribution of exposure along this strip is designated by the first

row of numbers below the curves which are in terms of the logarithm of the exposures given and are designated as "log E for A." Let the immediately adjacent area B be subjected to a similar exposure increasing logarithmically from left to right. The distribution of exposure on the strip B is designated by the second line of numbers below the curves, which is indicated as "log E for B." Let a third area C, which lies

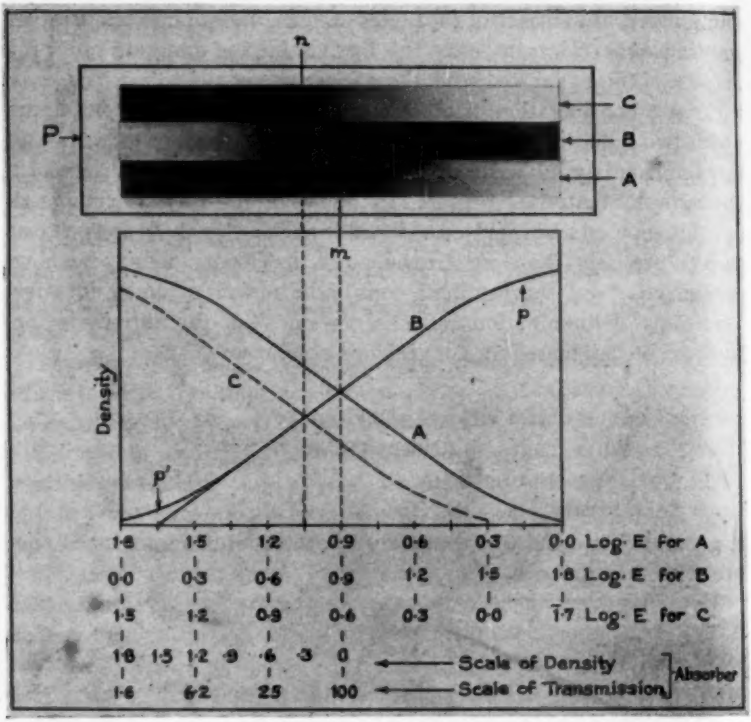

FIG. 1

immediately adjacent to B be subjected to an exposure increasing logarithmically from right to left and having the value as indicated in the third line of numbers below the curves and designated as "log E for C." It will be noted from these numbers that the exposure given to the area C is just one-half of that given to the area A. The exposure time t for every point on each of the three strips A, B and C is identical. The logarithmic variation in exposure is, therefore, the result of a

logarithmic variation in the incident intensity, I. The exposing radiation is monochromatic and the same for all three strips. Upon development a negative having the general appearance shown in the figure will be obtained. Development should be carried out in such a way as to obtain the maximum possible uniformity of action over the entire surface of the plate. Small departures from uniformity do not appreciably influence the validity of the results since equality of density ($D_1 = D_2$) is determined from very small (1 to 2 mm in diameter) immediately juxtaposed areas.

Inspection of the negative will show an equality of density between the deposits on strips A and B at m, while equality of density on strips C and B will be found at n. The linear horizontal displacement of the point n from the point m becomes a direct measure of the relative intensity of the radiation incident upon the strips C and A. This is evident from the inspection of the curves which are the characteristic curves of the three strips obtained in the usual way by plotting density, D, as a function of the logarithmic exposure, log E. The letters used to designate the curves correspond with those designating the three strips. It will be noted that a decrease of 50% in the intensity incident upon the strip C has caused the curve C to shift laterally by a distance equal to a logarithmic interval of .30. The intersection point of curves C and B, however, has shifted laterally from the intersection point of curves A and B by a log E interval of only .15. If we assume that the 50% decrease in the intensities incident upon the strip C was caused by the insertion of an absorbing element between the light source and the photographic material, then the density or absorbing power of this material is determined by the position of the point of density balance n relative to the point of density balance m. It is then possible to establish a density scale upon which it will be possible to read the density of any absorber of unknown density inserted between the light source and the photographic plate during the exposure of strip C. This density scale is shown in the fourth line of figures below the curves and is designated as "scale of density." This may also be given in terms of a transmission scale as shown. It will be noted that the gradient of the density with respect to distance, dD/ds, is twice as great as the gradient of exposure with respect to distance along the strips. With the conditions adjusted as shown in figure 1 the point of balance, that is the position of density equality for an absorber having a zero density, is at the middle of the plate and any absorber having a density greater than zero and less than 1.8 will give a point of density balance n some place

between m and the extreme left hand end of the exposed areas. It is evident that these conditions are not entirely satisfactory since one-half (the right hand portion) of the plate is useless as density indicating area. This undesirable condition can be corrected by increasing the intensity of the light source when exposing strips A and C so that the point of intersection of the curves or the point of density equality is shifted well over toward the right hand end of the plate. Thus if in exposing C and A the intensity be increased to 32 times that used in exposing strip B the intersection point of the characteristic curves or the point of density balance between A and B will be shifted to the line marked p. This line now becomes the zero point of the density scale for an absorbing media placed between the source and the photographic material during the exposure of C. In this way the entire length of the photographic plate becomes effective and the density scale for a given density range becomes much more open and therefore increases the precision with which the point of density equality can be determined. It should be noted that the requirements specified earlier in the paper for the determination of exact equality between radiation intensities have been fulfilled by this method.

The case shown in Fig. 1 illustrates the principle as applied to the general problem of measuring the relative intensities of radiation by use of the photographic plate. The same principle applied in any problem of photographic photometry will yield satisfactory results if the condition, that the radiation used in making all exposures is identical in spectral composition, is fulfilled. In the case of radiations which are not monochromatic, such as exist in the photometry of light sources under ordinary conditions, the condition that λ_1 shall be equal to λ_2 stated previously must be replaced with the condition that the spectral compositions of the two radiations compared be identical.

Fig. 2 shows more specifically how the method just described may be applied in spectrophotometric work. The diagram illustrates the usual dispersing system in a grating spectrograph. The entrance slit is designated as S, the collimator and projecting lenses as L_1 and L_2 respectively, and the grating by G. The photographic plate is shown at P, and in this particular case is so positioned as to receive the visible region extended from 400 mμ to 700 mμ. Between the photographic plate and the projecting lens L_2, and as nearly in contact with the emulsion surface of the plate as is possible, is placed the plate grid M. This consists of a series of vertical opaque strips equal in width to the space between adjacent strips. The width of strip used will depend upon the

optical characteristics of the dispersing system and will be governed by the wave-length interval which it is desired to maintain between the points at which density determinations are to be made. Since a grating gives normal dispersion a grid strip width of constant magnitude corresponds to a constant wave length interval in the spectrum. An elevation through the line *CD* is shown in the lower part of the figure. This plate grid is so arranged mechanically that it can be moved along the line *CD* by a distance exactly equal to the width of grid strip or space.

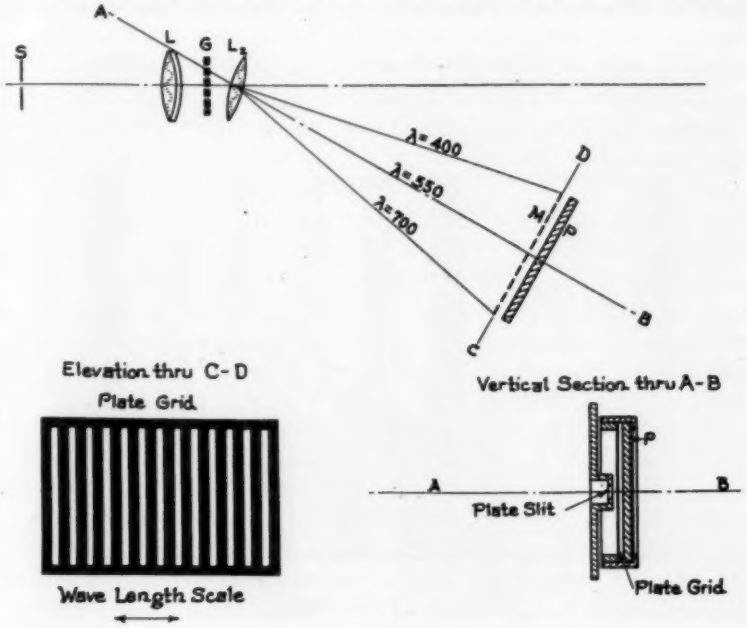

FIG. 2

This provides a means whereby alternate narrow bands of the photographic material can be exposed while a series of exactly similar interspaced narrow bands covered by the opaque grid strips is protected from exposure. Then by shifting the plate grid by the width of a grid strip, the bands lying between those already exposed can be subjected to an exposure through the filter or absorbing medium, of which the spectrophotometric characteristic is to be determined. If the exposure given with the grid plate in its initial position be logarithmically graduated in one direction and the exposure given after the grid plate has been shifted laterally by a distance equal to the width of a grid

strip be graduated logarithmically in the opposite direction, the plate upon development will have an appearance similar to that shown in Fig. 3 and will consist of a series of narrow bands having a graduated density in one direction interlaced with another series of bands having a graduated density in the opposite direction. Referring now to Fig. 3, let it be assumed that the exposure given with the grid plate in its initial position be indicated by the numbers in the column designated as log E_a, while the exposure given with the grid plate in its second position are referred by the numbers in the column designated as log E_b.

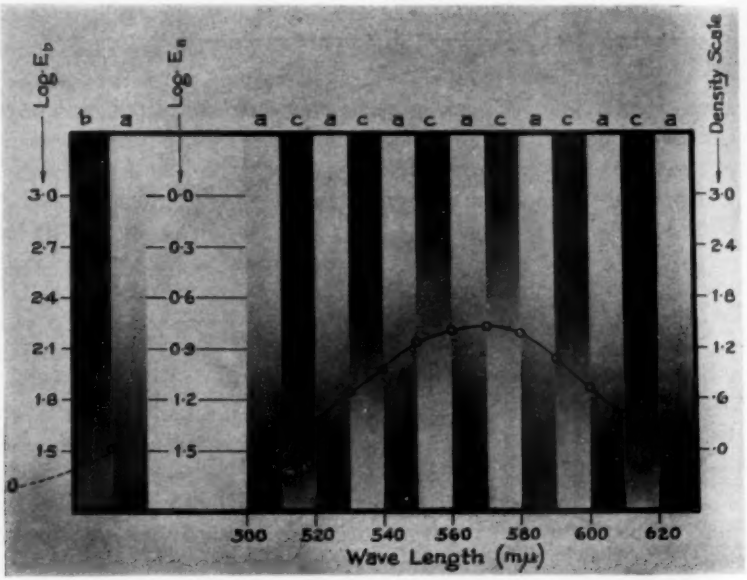

FIG. 3

It will be noted that the actual exposure intensity for strip *b* is equivalent for strip *a* at the point marked *O*. The position of this point then determines the position of the zero point on the density scale shown at the right of the figure. Areas *a* and *b* in Fig. 3 represent any pair of strips regardless of the position in the spectrum. The actual density values may be different at different points in the spectrum and the actual density gradients may also vary but the position of equality of density must lie at the same point for all pairs of strips exposed as specified above.

The series of strips designated as *c*, *c*, *c*, etc. and the alternate strips designated as *a*, *a*, *a*, etc., show the conditions when an absorber is placed in the path of the exposing radiation during the exposure with the grid plate in its second position. As indicated in this drawing each grid strip is equivalent to a wave-length interval of 10 mμ. If now, at each dividing line between adjacent strips, the position of density equality be determined, the position of these points relative to the horizontal line drawn through *O* will determine the density of the absorbing material at the various wave-lengths. In the particular case illustrated in Fig. 3 the points lie as shown and the line drawn through these points form the spectrophotometric density curve of the materials used. The density scale at the right of the figure is established as previously described, the gradient of filter density with respect to distance being equal to twice that of the gradient of exposure with respect to distance along the strip.

A temporary instrument was assembled to try out this principle and the results, while not entirely satisfactory on account of the rather crude mechanical construction, were so promising that it is proposed to construct a finished instrument operating on this principle. The most difficult problem is to devise a satisfactory means for obtaining an exposure graduated logarithmically from top to bottom, and vice versa, of the photographic plate. After carefully considering various possibilities it was decided to do this by the use of a radial sector diaphragm operating over the collimating lens, which can be opened or closed automatically at the required logarithmic rate. For this purpose a radial sector diaphragm having a maximum possible opening of 300 degrees has been designed, thus objectionable loss of light occurring with diaphragms of this type having a maximum opening of 180 degrees is to a large extent eliminated. The radial type of diaphragm was adopted in preference to the annular or iris type since it completely eliminates any intensity errors due to zonal lens abberations. The idea of using an absorbing wedge either at the slit or in front of the photographic plate was rejected since it was not possible to obtain elements of this kind which are entirely nonselective in their absorbing characteristics. Several other methods of producing the logarithmically graduated exposure were considered but after careful analysis the radial sector diaphragm was adopted as being the most free from objections.

Simultaneously with the opening or closing of the collimator diaphragm the photographic plate is moved up or down at a uniform linear velocity past a horizontal slit lying in the spectrum plane and

immediately in front of the photographic plate and the grid plate. The relative position of this plate slit is shown in the lower part of Fig. 2, which is indicated as "Vertical section through line *AB*." The photographic plate and the grid plate are supported in the same carriage and move up and down together past the slit as indicated. The width of the plate slit can be varied somewhat in order to control exposure time. Since the plate moves at a uniform linear velocity and the slit is of uniform width for all wave-lengths, the exposure time t is the same for every point on the exposed photographic plate. The closing or opening of the collimating lens diaphragm at a logarithmic rate results in a logarithmic change in the intensity incident upon the plate at various points. If the collimator diaphragm be allowed to start at maximum aperture and close while the plate is moving downward and with the plate grid at its initial position a series of parallel strips having a maximum density at the bottom of the plate and decreasing upward as shown in strips *a*, *a*, *a*, etc., Fig. 3, will be obtained. Now if the plate grid be moved laterally to its second position the collimator diaphragm reset to its maximum aperture and allowed to close logarithmically while the photographic plate moves upward, a series of interlacing strips having a maximum density at the top and decreasing downward, such as is shown in *c*, *c*, *c*, etc., Fig. 3, will be obtained. It is proposed to operate the collimator diaphragm and the photographic plate by means of properly cut cams as shown in Fig. 4. The satisfactory performance of such an instrument depends very much upon the mechanical perfection with which it is constructed. It is proposed to use very rigid lathe bed on which to construct the mechanism. There are many details of design which require very careful attention. A discussion of these does not seem necessary for the purposes of this paper. In the instrument which has been designed the wave-length range from 350 mμ to 750 mμ is included. The plate grid strips are of a width equivalent to a wave length interval of 5 mμ so that a density determination can be obtained for each 5 mμ interval.

The question of determining the point of balance with maximum precision has also been given consideration. This can be done by a visual comparator but it is proposed to use for this purpose a physical photometer employing either a thermopile or photoelectric cell as receiving element. It should be noted that it is not necessary to make measurements of photographic density, but merely to determine the point at which density equality exists. A null method can therefore be used, and all of the many troublesome details of absolute density

measurement are avoided. A physical photometer which has already been constructed and is in use in this laboratory is sensitive to 0.20% difference in density and there is little doubt that this sensitivity can be increased further if necessary. There seems to be little doubt therefore, that the position of density equality can be determined with an uncertainty much less than the unavoidable errors at other points.

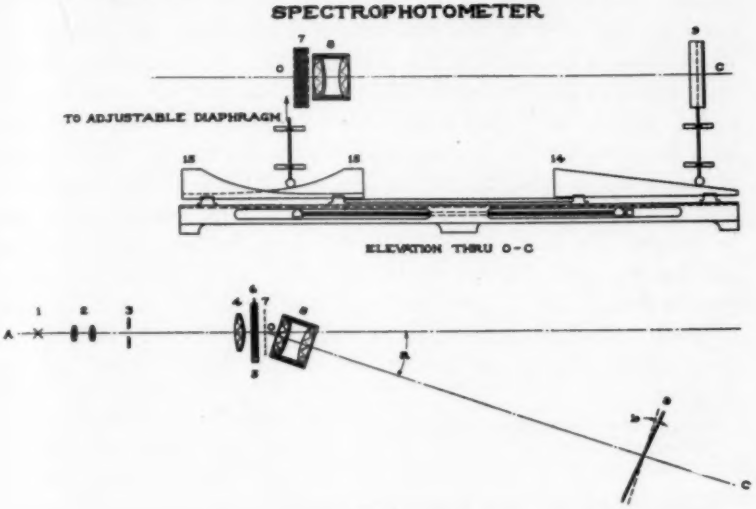

FIG. 4

It will be noted by referring to Fig. 3 that the spectrophotometric curve as plotted directly on the negative is of the form in which such curves are usually plotted, hence this curve may be transferred directly to coordinate paper having the same density and wave-length scales. This is very convenient since it is possible, by attaching a recording point, such as pencil or stylus, to the moveable frame which carries the negative on the density comparator, to plot the curve directly while the points of density equality are being determined. This point being carried on a rigid arm extending from one side of the negative carriage travels over the surface of the coordinate paper placed on a suitably located table. The negative in its carriage is moved back and forth in a direction parallel to the exposure bands until the photometer shows an equality of density between two of the adjacent strips. The marking point then being depressed, records on the coordinate paper the value of density at that wave-length. In this way the filter density values

are recorded directly upon the coordinate paper and when a curve is drawn through the points thus recorded the required spectrophotometric density curve is at once obtained.

The extent to which the exposed plate is developed has very little influence upon the results except that the greater contrast will increase the precision with which the point of density equality can be determined. The operation of the method is entirely independent of the characteristic curve of the materials used and makes no assumption whatever as to the shape of this characteristic. No necessity exists for confining the measurements to the straight line position of the characteristic curve, and in fact a characteristic having no straight line will serve just as well as one having a long straight line region. For purposes of record and in case the greatest precision is not required, very satisfactory representations of the spectrophotometric density curve can be obtained by making contact prints from the negatives. If this printing is properly carried out in such a way as to equalize the variations in density due to variation in spectral sensitivity of the material and with a superposed scale plate in proper position, a very satisfactory direct production of the spectrophotometric density curve can be obtained.

EASTMAN KODAK RESEARCH LABORATORY,
ROCHESTER, N. Y.

Point-Discharge Ion Counter.—The question is, why the point-discharge initiated by the passage of an ion across the chamber containing the pointed electrode, being apparently of the self-sustaining type, should spontaneously cease. Geiger suggests that the metal forming the pointed electrode is covered with a high-resistance sheath, so that when the discharge-current is established a large fraction of the battery emf is consumed in establishing the potential drop across the sheath, not leaving enough voltage across the gap from point to collector to maintain the discharge. To sustain this theory Geiger offers data to show that when circumstances are varied by altering the capacity shunted across the gap, in each case the discharge continues until a certain constant quantity of charge has flowed out through the point. The theory is in opposition to Kutzner's reviewed heretofore (This Journal, *9*, p. 674, 1924), but the specific facts adduced by Kutzner to support his theory do not seem to be explained by Geiger's. [H. Geiger, Charlottenburg; ZS. f. Phys. *27*, pp. 7-12; 1924.]

KARL K. DARROW

A MICROTURBIDIMETER

By O. E. Conklin

I. INTRODUCTION

The disappearance of a test object has for many years been employed as a means for comparing the turbidities of different liquids. In expressing the results of such comparisons, numbers inversely proportional to the thickness of the thinnest layer which will obscure the test object are used to indicate the relative turbidities. Holker,[1] using the disappearance of a wire mounted below the turbid liquid, has shown that turbidity is proportional to concentration for various turbid cultures of bacteria, while experiments conducted in the Research Laboratory of Messrs. Ilford, Ltd., in England under Mr. F. F. Renwick using a uniformly repeated pattern set diagonally across a 1 cm thick cell about 15 cm long have established the same relation for dilute photographic emulsions. These observations have since been confirmed in this Laboratory with several types of photographic emulsions. An experiment mentioned in this paper shows that it also holds for the instrument about to be described with concentrated photographic emulsions. From these instances, we may conclude that several turbidimeters differing widely in design give relative turbidities which are proportional to concentration. From this relation, it follows that for a particular turbid medium, the product of the obscuring thickness and the concentration is a constant for a given instrument and that these products are typical of the materials, since each represents the maximum area of the test object used in the turbidimeter which can be obscured by unit mass of the particular dispersoid to which it refers. In what follows numbers inversely proportional to obscuring thickness and given by $10/t$, where t is in millimeters are called relative turbidities, while values corrected for concentration by use of the formula $T=10/tc$ are called specific turbidities. Of course, it should be understood that the values of specific turbidity refer only to the particular instrument employed and depend on the nature of the pattern obscured and other optical features of the design. Such specific turbidities represent, however, the inherent covering powers of the various turbid media and depend mainly on the average size and other optical properties of the particles in suspension. For a given material, specific turbidity increases with decreasing particle size

[1] Biochem, J. *15*, pp. 215-225, 1921.

until their diameters approach the wave length of light, after which it decreases again.

Relative turbidity measurements have long been used by chemists in the quantitative estimation of minute quantities of material in suspension on the assumption that the specific turbidity of the precipitate was constant even with considerable variations in the method of its formation, which is seldom the case. The reference already made to work done at Ilford and this paper are in themselves sufficient evidence that variations in the specific turbidity of one and the same material according to the method of precipitation are now receiving close attention.

While at first the disappearance of a test object seems a somewhat vague criterion for turbidity, it is not found very difficult in practice, and is less affected by the color of the medium than a photometric measurement of the scattered light. A straight incandescent lamp filament gives a most satisfactory test object. For low turbidities, layers of considerable thickness are required, and the measurement of these thicknesses offers no difficulties. However, many suspensions and emulsions of considerable industrial importance are so turbid that a layer only a fraction of a millimeter thick obscures the filament. To measure accurately the obscuring thicknesses of such media, we have found the most convenient cell to be a lens pressed against a flat glass plate.

A new turbidimeter using this cell has been designed for making rapid routine measurements on photographic emulsions without preliminary dilution of the samples. As but a drop of emulsion is required, we have named this instrument the "microturbidimeter."

II. DESCRIPTION OF THE INSTRUMENT

The cell consists of a four diopter plano-convex lens placed convex side downwards on a piece of plate glass. There is only one point of contact between the lens and the plate. They are held together by a brass frame as shown in Fig. 1. The sample fills the space between them, its thickness increasing outwardly from the contact point. The cell is placed over a lamp having a long straight filament in such a way that the filament crosses the point of contact. When viewed through the cell, the filament can be clearly seen through the point of contact but it gradually fades out in each direction, due to the increasing thickness of the sample. At a certain distance in either direction from the point of contact, it disappears altogether. From the distance, S, between the disappearance points, the thickness t, of the sample required to obscure the filament is given by the formula, $t=S^2/8r$, where r is the radius of curvature of the lens.

The simplicity of the cell used in this turbidimeter makes it easy to clean, to fill, and to duplicate. If the sample is fluid it is run between the cell walls with a pipette, if viscous a drop of the sample is placed on the plate and the lens is squeezed down on it. Since there is only one point

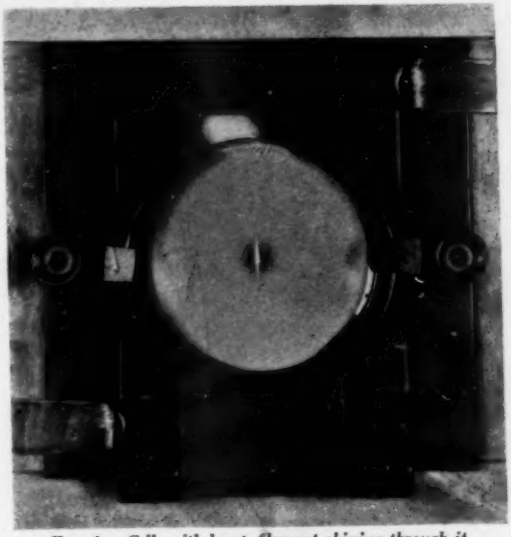

FIG. 1. *Cell, with lamp filament shining through it.*

of contact, errors from bad contact between the cell walls are easy to avoid. A large number of duplicate cells can be prepared at moderate cost, thus facilitating routine measurements.

FIG. 2. *The microturbidimeter.*

In order to measure the distance, S, between the disappearance points of the filament, the instrument shown in Fig. 2 has been devised. It is

essentially a low power microscope provided with a lever about 30 inches long which serves as a mechanical stage and as a device for magnifying and recording the settings. The fulcrum of the lever is 2-1/2″ to the left of the center of the microscope. Its free end is provided with a phonograph needle with which the settings of the lever can be pricked on a record sheet stretched between two rolls. A ratchet mounted on the wind-up roll, which is an old typewriter platen, assists in providing an even spacing between the needle pricks.

The lamp is mounted below the stage of the microscope with its filament at right angles to the lever arm. Openings in the lever arm and its support permit one to focus the microscope on the filament. The mounting of the lamp is shown in Fig. 3. It is provided with adequate

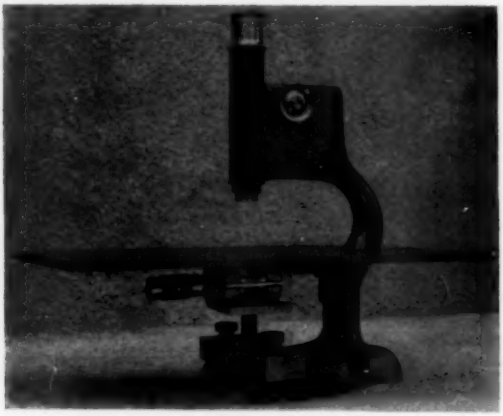

FIG. 3

adjustments for centering the filament under the microscope and set screws for holding it in place. The lamp is of special construction having a cylindrical bulb with a single straight filament running along its axis. It is rated at 6 volts and 2.1 amperes and is run on a small transformer, its current being kept constant at 1.3 amperes by means of two ballast lamps connected in series with it. Both the special lamp and the ballast lamps were furnished by the Westinghouse Lamp Co.

The microscope is equipped with a 48 mm objective and a 10X eyepiece with cross hairs. To obtain the best results, it was found necessary reduce the field of the eyepiece to half its normal size in order to cut off the bright part of the image while making a setting, and to reduce

the aperture of the objective to a slit 0.5 mm wide running at right angles to the filament so that all the rays forming the image of either disappearance point pass through substantially the same thickness of the sample.

III. TECHNIQUE OF MEASUREMENT

In operating the microturbidimeter, the cell is filled with the sample and placed on the lever as shown in Fig. 2. The lever is moved to its central position, the microscope is focused on the cell which is then centered by moving it until the contact point is in the center of the field. The draw tube is racked down until the filament is in focus, the lever is moved away from the observer, carrying the cell with it until the filament just disappears from the upper half of the field, and the position of the lever is recorded by pressing its pointed end against the record sheet. Then the lever is moved towards the observer until the filament disappears from the lower half of the field and its position is again recorded by pressing it against the sheet. Five such pairs of settings are made, the record sheet being shifted between each pair of settings, and best representative lines are drawn respectively through the upper and lower groups of points, and from the distance, d, between them is computed the relative turbidity of the sample by means of the formula $T = K/d^2$ where T = relative turbidity and K is a constant.

In order to maintain consistency over considerable periods of time, it is desirable to correct the observed turbidities for the variable personal equation of the observer. This is determined by taking readings on a turbidity standard before and after measurements on each lot of samples. The ratio of the accepted value for the turbidity of the standard to the observer's value gives a factor by which the observed turbidities are multiplied to correct for such fluctuations on the part of the observer.

The turbidity standard we employ consists of a piece of flashed opal glass in which a concave lens has been ground just cutting through the opal coating. To eliminate all lens action, the hollow is filled with Canada balsam and covered with a plate of glass.

IV. REPRODUCIBILITY OF TURBIDITY MEASUREMENTS

We find that after correcting for the personal equation by means of readings on a standard turbidity, turbidity measurements can easily be reproduced within 2 per cent. With careful work, the average deviation of a single observaton is better than 1 per cent. The following data,

taken in calibrating a series of 10 cells, illustrate the reproducibility both of turbidity measurements and of the cells. In making these measurements, samples of the same photographic emulsion were placed in each of the ten cells, and the turbidities were measured. On the following day, check tests were made on seven of the cells, the remaining cells being checked on the third day.

TABLE 1. *Reproducibility of Turbidity Readings*

	Observed Turbidities			Corrected Turbidities			
	1st Day	2nd Day	3rd Day	1st Day	2nd Day	3rd Day	Differences
Turbidity Standard	162.4	162.0	167.0	159.5	159.5	159.5	
Cell No.							
1	141.2	140.2		138.7	138.1		− .6
2	142.4	142.2		139.9	140.1		+ .2
3	141.8	141.0		139.3	138.9		− .4
4	142.2	142.0		139.7	139.9		+ .2
5	141.2	141.8		138.7	139.7		+1.0
6	141.0	141.6		138.5	139.5		+1.0
7	141.6	141.8		139.1	139.7		+ .6
8	141.8		146.6	139.3		140.1	+ .8
9	141.6		146.8	139.1		140.4	+1.3
10	142.2		145.8	139.7		139.4	− .3
	Averages			139.2	139.4	140.0	.66
	Av. Deviations			± .36	± .53	± .37	
	Per cent Av. Deviations			.26	.38	.26	

V. RELATION BETWEEN TURBIDITY AND CONCENTRATION

As pointed out in the introduction to this paper, the proportionality between turbidity and concentration has been definitely established within the limits of experimental error for dilute suspensions. In order to test this law for the high concentrations which fall within the range of the microturbidimeter, portions of a photographic emulsion were diluted to a series of different concentrations, and the turbidity of each portion was measured on the microturbidimeter. The results, which are given in Table 2, show that the proportionality between turbidity and concentration held within the limits of experimental error.

TABLE 2. *Relation between Turbidity and Concentration of Silver Halide in a Photographic Emulsion*

Per Cent Silver Halide	Relative Turbidity	Ratio of Turbidity to Concentration
0.95	22.5	23.7
1.44	33.7	23.4
1.76	41.3	23.5
2.24	53.7	24.0
2.65	62.5	23.6
2.99	70.0	23.4
3.44	81.4	23.7
3.95	89.6	22.7
4.51	104.2	23.1
5.21	122.0	23.5
	Average	23.5
	Av. Deviation	.24
	Per Cent Av. Deviation	1.0

VI. APPLICATIONS

Table 3 is intended to show the variety of materials whose turbidities can be measured on the microturbidimeter. The thickness of the material which just obscures the filament and the relative turbidity is given for each material examined, and where the concentration of the dispersoid was known, the specific turbidity is also given.

TABLE 3. *Obscuring Thicknesses, Relative Turbidities, and Specific Turbidities of Various Materials*

	Concentration of Dispersed Phase in Grams per cc $=c$	Obscuring Thickness in mm $=t$	Relative Turbidity $=10/t$	Specific Turbidity $=10/tc$
Slow Photographic Emulsion	0.050	.13	77	1500
Fast Photographic Emulsion	0.050	.24	42	830
White Enamel	0.30	.031	320	1080
Black Enamel	0.038	.041	250	6400
Gray Enamel	0.090	.098	102	1140
Blue Enamel	0.070	.23	44	620
Bronzing Liquid	0.15	.53	19	130
Cream	—	.024	420	—
Milk	—	.19	54	—
Evaporated Milk	—	.16	61	—
Butter	—	.14	71	—
Lard	—	.59	17	—
India Ink	—	.043	230	—

It is evident from this table that the microturbidimeter can measure the turbidities of many substances for which there has previously been no convenient instrument. In none of these measurements was it necessary to dilute the sample.

Among its possible uses are:

1. The determination of butter fat in cream, and the grading of dairy products.
2. The standardizing of pigments with respect to particle size. Since turbidity is dependent on the average size of the particles in turbid media, it can be used as a means of controlling their fineness.
3. The determination of the covering power of paints, enamels, etc.
4. The study of bacteriological cultures.

The author wishes to express his thanks to Mr. F. F. Renwick, Director of Redpath Laboratory, for guidance in the study of the turbidity of photographic emulsions, and to Dr. P. V. Wells for his advice and criticism.

REDPATH LABORATORY,
E. I. DU PONT DE NEMOURS & CO.,
PARLIN, N. J.
NOVEMBER, 1924.

Polarization of Resonance Radiation by Magnetic Field.—By using a powerful spectrograph Gaviola and Pringsheim separated the D-lines in the resonance-radiation excited in sodium vapor by unpolarized light, and observed from the direction normal to the direction of propagation of the primary beam. Applying a magnetic field parallel to the direction of the primary beam, they observed (with the aid of a Savart plate) that D_2 is partially polarized and D_1 not at all, which is in accordance with theory. The percentage of polarization of D_2 is independent of whether or not the primary beam is polarized; when the vapor density is as low as it can be made without the light becoming too faint to measure, the polarization increases with increasing field strength to a maximum of 24% which it attains at about 200 gauss; when it is considerably denser (sodium maintained at 190°C) the degree of polarization is much smaller and increases steadily with increasing field strength up to at least 600 gauss. This effect is supposed to be due partly to overlapping atomic magnetic fields, and partly to collisions of the "second kind," which when undergone by atoms which have absorbed energy from the primary beam cause them to yield it up otherwise than in resonance radiation. [E. Gaviola and P. Pringsheim, Berlin; ZS. f. Phys. *25*, pp. 367-377; 1924.]

KARL K. DARROW

A LOW-VOLTAGE ELECTRON-BEAM OSCILLOGRAPH

By J. W. Buchta

During an attempt to measure the scattering of electrons after collision with mercury atoms it was discovered that the electron stream from the source did not widen out as might be expected but remained in a sharply defined, narrow, visible beam. Two diaphragms 7 mms apart with holes about .7 mm in diameter were used in the "electron gun" which will be described later. The electron beam remained about 1 mm in diameter, even at a distance of 30 cm while the diameter of the cone of light from the filament was 4 cms or larger. It is the purpose of this paper to give a description of this beam, the apparatus necessary to produce it and some of its possible uses.

In several recent thermionic Braun tubes and oscillographs a similar concentrated beam of electrons has been described.[1] In the instrument developed by Johnson it was found that the introduction of argon at a low pressure kept the electron stream from diverging and made it possible to focus the stream at a desired point by adjustment of the filament temperature. To explain the action of the gas it is assumed that the argon atoms are ionized by collision and that within the electron stream a core of positive ions is formed. The mobility of these positive ions is much smaller than that of either the impinging electrons or those removed from the atoms by collision. This difference of mobility allows the electrons to move out of the path of the electron stream much more rapidly than the positive ions do. There then results an excess positive charge within the beam and an excess negative charge in the region outside. A radial field is thus set up which tends to overcome any diverging of the stream of electrons and causes it to remain narrow and well defined. Evidence in support of this explanation was given by Johnson and it is believed that still more conclusive evidence has been found in the present investigation.

Jones and Tasker used an electrostatic focusing arrangement besides using mercury vapor which no doubt acts in the same manner as the argon in the tube described above. In each of these tubes the electrons attained a velocity corresponding to 300 volts before striking the fluorescent screen.

[1] Johnson, J. B., J.O.S. & R.S.I., *6*, p. 701; 1922.
Jones and Tasker, J.O.S. & R.S.I., *9*, p. 471; 1924.

DESCRIPTION OF PRESENT TUBE

The beam of electrons here described differs from those in the tubes mentioned above, in that the electrons have velocities corresponding to 30 volts or less and the beam is visible and sharply defined throughout its length.

A diagram of the tube used to produce it is shown in Fig. 1, drawn to scale except for length. Tubes of varying lengths have been used. One, about 30 cms long was found to be very satisfactory.

The "electron guns" E_1 and E_2 are usually placed well within the nickel gauze G in order to avoid space charges as much as possible. This gauze is electrically connected to the anode of the electron gun. The side tube with the quartz window Q permits a study of the spectrum of the beam. The plate P is of plane glass sealed on the end of the tube.

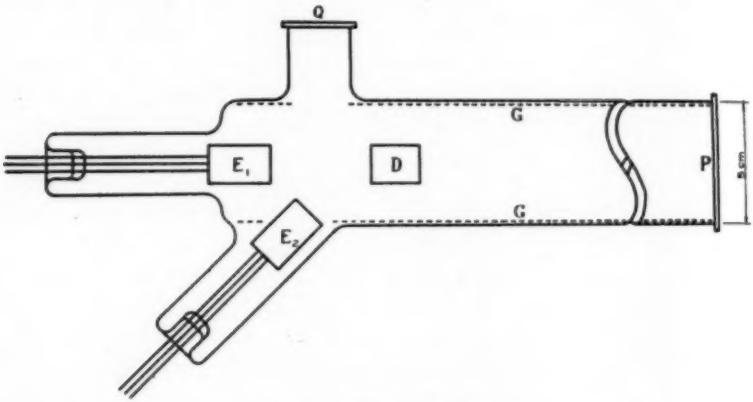

FIG. 1. *Diagram of the tube*

The electron gun E_2 is used when it is desired to photograph the spot produced on the plate P. It is set at an angle so that the light from the hot filament cannot shine directly on the plate P. By means of a permanent magnet the beam is easily deflected so that it reaches the plate. When it was desired to photograph the beam and to study the effects of the charges that would collect on the exposed glass wall a part of the shielding gauze was cut away. The deflector plates D are used to obtain electrostatic deflections.

The electron gun is shown in section in Fig. 2, drawn to scale. The metal parts of it are all of nickel, the essential parts being coaxial

cylinders with suitable diaphragms. The filament F is made of tungsten wire (.2 mm) shaped into an "N" and placed about 1 mm from the first diaphragm D_2. A metal shield S is placed around the filament and connected to the negative filament lead. Between this shield and the first cylinder carrying the diaphragm D_2 is a short glass tube, I, used for insulation. This is double cross-hatched in the figure. The final outer cylinder carrying the diaphragm D_1 is welded to a ring placed around the first cylinder with holes drilled through it, allowing ample openings for any accumulated gas to escape from the space between the two diaphragms. The distance between the diaphragms is about 7 mms. The filament leads pass through a metal cylindrical block, B, one of them being insulated from it by a glass tube. The shield S is welded to this block and holes are drilled through it to permit the escape of any gas from the filament space. A third lead is connected to the two cylinders and diaphragms which serve as an anode. The

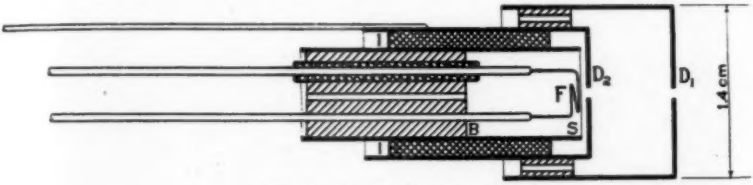

FIG. 2. *The "electron gun"*

holes in the anode diaphragms are about .7 mm in diameter. The three leads serve as support for the whole unit.

It is essential that the electron emission from the filament be high. But even with the high filament temperatures used and the presence of mercury vapor, the filament life is fairly long. A filament has run over 100 hours under varying experimental conditions that were sometimes very severe. The low voltages used and the very small space between the hot filament and anode are no doubt an aid to long life.

THE ELECTRON BEAM

The low electron velocities used in this beam make it very sensitive to electric and magnetic fields. Used in a Braun tube it is possible to secure with one volt difference in potential between deflector plates a deflection of about 8 mms from the zero position with a beam 25 cm long. Such a tube has a correspondingly high magnetic sensitivity. If turned about in the earth's field the changes in the radius of curvature of the beam are easily detected.

The beam has a bluish color and is bright enough to be distinguished in a well lighted room. No fluorescent screen has been found necessary in using this beam. Its own luminosity and that of the spot where it strikes the glass wall are sufficient for photographic purposes.

Fig. 3 is a full size photograph of a portion of the beam. A part of the shielding gauze was removed so that the beam may be more clearly seen. The electron gun is at the left hand end. The photograph was taken on a Graflex 60 plate, exposure 1.5 min. and stop U. S. 4 was used. The difference of potential between cathode and anode was 27 volts.

There are usually one or more distinct focus points along the beam. With several of these points present the beam has the appearance of a vibrating string with loops and nodes. Fig. 3 shows one of these focus points very clearly. They may be caused to move along the beam by adjustment of the filament temperature or of the accelerating potential between cathode and anode. By proper adjustment one of these

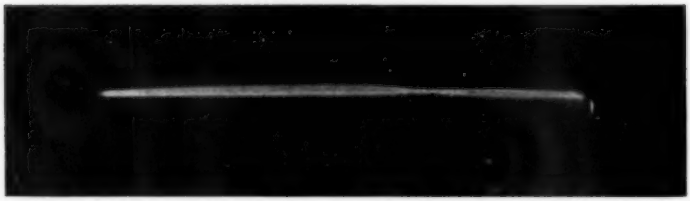

FIG. 3. *Photograph of the beam*

focus points can be made to come at the end of the beam where it strikes the glass plate and thus a very small, sharp spot is obtained.

The tubes in which this beam has been used were usually left connected to a mercury condensation pump and the pump operated whenever the filament was lighted. The tubes were therefore filled with mercury vapor at a pressure corresponding to room temperature. The most clearly defined beams are obtained with mercury vapor at room temperatures. With higher vapor pressure obtained by heating, the beam becomes diffuse and arc conditions are approached. However, at room temperatures and with the electron gun as finally made, there were no difficulties due to an arc forming. If the space surrounding the hot filament was not made small and fairly well enclosed an arc could be formed with high electron emission.

That mercury vapor was essential for the luminosity of the beam was demonstrated by applying liquid air to a trap in the vacuum line.

After its application for a short time, depending on the amount of mercury condensed in the tube, the beam became invisible. As soon as the liquid air was removed and the trap warmed the beam reappeared. The light from the beam when analyzed by a Hilger Quartz Spectrograph showed the mercury spectrum.

Fig. 4 shows a photograph of the beam bent by the magnetic field of a bar magnet brought near it. The outline of the tube was sketched on the negative. The shielding gauze G was for this photograph placed some distance away from the electron gun E_2, allowing a part of the beam to be seen through the glass only and a part through the gauze as well. The beam is bent toward the wall of the tube striking it at an angle. This causes a larger spot on the glass than when it strikes

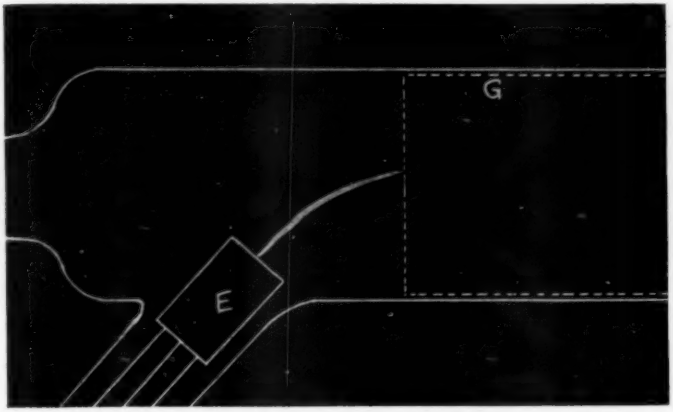

FIG. 4. *The beam bent by a magnetic field*

directly. The spot on the glass usually appears brighter than the beam itself and of a slightly different color. The spectrum of it, however, shows the same lines as the beam and in addition a band in the visible region. The potential applied in this case was 22 volts. The reproduction is about three quarter size.

By bringing several magnets near a very complex magnetic field may be produced and as a result the beam may be bent into curves of almost any form desired. Even when the radius of curvature of these curves is very small at some points or when the beam is twisted into figure "8's" or other curves of even greater change in direction and in curvature, the beam remains sharp and well defined. If a fine wire is

connected to the anode and placed in the tube along the path of the beam, it will follow the wire curling around it in such a manner that one is reminded of a stream of water flowing down a glass rod.

EVIDENCE FOR THE POSITIVE ION CORE

If the existence of this narrow beam is to be explained in terms of a high density of positive ions, one would expect the spark lines of the mercury spectrum to be present. On some of the photographs taken of the spectrum, several lines appeared that were not present in the spectrum from a quartz Lab-Arc even on long over-exposure. One of these, and usually the strongest, was λ2848A which is assigned by Fowler[2] to the spectrum of ionized mercury. It was found with an electron velocity of 25 volts but not in cases where the velocity was below 20 volts. Exposures were made to give the same intensity of the adjacent arc line λ2857A. The line λ2848A was usually more intense than the arc line λ2857A with electron velocities above 25 volts.

FIG. 5. *Effect of space charges*

Three or four other lines were found that are not present in the usual arc spectrum. It is believed that this beam may provide a convenient method of producing spark lines and of determining their excitation potentials. The presence of the spark lines with relatively high intensity when the electrons have 25 to 35 volts velocity is also believed to be good evidence of the positive ion core postulated for the beam.

The fact that the beam is so luminous is in itself evidence of the presence of the positive ions. In a darkened room the beam may be seen 20 to 25 ft. away.

EFFECTS OF SPACE CHARGES

Space charges show themselves very markedly in this apparatus. To obtain a long beam below 30 volts the glass walls must be shielded. Fig. 5 shows the result when the glass walls are not shielded. The electron gun is at the left hand end.

[2] Report on Series in Line Spectra. The Physical Society of London, 1922.

Some distance up the tube a metal plate is placed in the path of the beam and connected to the anode. For a short distance from the electron gun the beam is visible, then it disappears to reappear in the region of the metal plate. But here it is broad and diffuse. This portion is shown on the right hand end of the figure, the sharp end of the diffuse beam marking the surface of the plate. These effects may be explained in terms of a charge building up on the glass walls and in the enclosed space, producing a retarding field. The electrons are reduced to a velocity less than 10.4 volts over a part of their path and hence, since they cannot ionize the mercury vapor, this part of their path is invisible. As they approach the plate, the electric field is reversed in direction and the electrons are accelerated toward the plate. In the case photographed they attained sufficient velocity to ionize the vapor some distance in front of the plate and the path of the stream of electrons becomes visible again. The broadening of the beam after ionization has ceased is to be expected if the positive ion explanation of the fine beam is correct.

The presence of the charge on the glass walls is shown by placing an insulated electrode in the tube and near the glass wall. It will take up the potential of the hot filament,—that is, a negative potential with respect to the anode, the difference in potential between the insulated electrode and anode being equal to that through which the electrons have fallen.

There is, with a very high electron emission, a glow surrounding the beam. With the glass walls insulated as mentioned above, this glow also ends abruptly, with the beam just reaching the curved end of the glow. One would expect the line λ2537A to be found beyond the edge of the visible glow and beam since the electrons could excite this line until their velocity was reduced below that corresponding to 4.9 volts. The spectrograph showed this line extending a centimeter or more beyond the end of the beam, and much stronger in the path of the beam than in space surrounding it. The radiation of λ2537A may be handed on in mercury vapor so that one would not expect as sharp an edge to the region in which it was found, as is the case for the visible light. A picture taken by means of a camera with a quartz lens showed considerable light beyond the sharp edged visible region and also showed the beam to continue beyond this edge but with boundaries not so well marked.

CONDITIONS NECESSARY FOR THE BEAM

The essential conditions necessary for the production of a good beam at low voltages may be summed up as follows: (1) a well shielded space so that space charges do not prevent its formation, (2) presence of mercury vapor for production of the positive ions, (3) a high electron emission, and (4) a small and fairly well enclosed space between the hot cathode and anode to prevent an arc forming.

USES OF THE BEAM

The tube may be used as a low voltage cathode ray oscillograph. The sensitivity is comparatively high and the spot on the end plate sufficiently bright to render a fluorescent screen unnecessary. On account of space charge effects a steady small voltage applied to the deflector plates does not produce a steady deflection of the beam. At the instant of application of the voltage the beam is deflected but immediately it begins to straighten out and, usually within 5 to 10 seconds, passes between the plates as if they were at the same potential. This is due to an ionic layer or sheath[3] forming on the electrode surface and completely shielding the beam from its charge. Deflector plates placed outside the tube in a position where the inner shielding gauze was removed had very little effect on the beam. The difference in the effects observed by Jones and Tasker[4] between the cases where internal and external deflector plates were used is no doubt to be explained in terms of these ionic sheaths and space charges. Jones and Tasker did not have such intense ionization in their tube as is present in this tube so that they could use external deflector plates. They did, however, observe that the amplitude of the electrostatic deflection with external plates could be varied at will by simply altering the electron emission, especially at low frequencies. The shielding of the charge on the walls of the tube would be a function of the intensity of ionization in the tube, so that one would expect the effects they found. With internal deflectors and high enough frequencies these effects were not observed. A more complete study and development of the present tube as a high frequency oscillograph is being made by Mr. E. D. Wells of this laboratory.

Besides its numerous uses in a low voltage oscillograph, we have found this low voltage beam useful in other ways. It serves very well

[3] Langmuir, G. E. Review, *26*, p. 731; 1923.
[4] Loc. cit.

for demonstration lecture purposes, particularly so since the beam is visible. First it demonstrates in a very realistic manner the emission of electrons by a hot filament and qualitatively how this varies with temperature. A small increase in the filament current after the first noticeable emission greatly increases the intensity of the beam.

The deflection of moving electrons in a magnetic field is very clearly demonstrated. The beam may be bent into complete circles or other figures of various shapes, still maintaining its small diameter and sharp edges. The principles involved in e/m measurements, beta ray spectra and isotope determinations are very clearly illustrated. In fact, rough calculations of e/m may be made.

The presence of space charges and their effects are easily shown. The beam may be bent into a curve, a part of which extends out in a region where the space charges are effective and by proper adjustment of the electron velocities the beam may be made to become invisible in that part of its path. The velocity of the electrons is there reduced below that required for ionization. Extrapolating from the parts of the beam that are visible, it is seen that the radius of curvature is smaller in the dark region. The presence of the ionic sheaths discussed by Langmuir can be demonstrated as mentioned above.

The phenomena of critical potentials can be shown in a very clear and striking manner. By careful shielding of the beam one can determine the ionization potential of mercury vapor to within .2 of a volt. This is done by reducing the accelerating voltage, when one finds that the visible beam just disappears as the ionizing potential is reached. The filament drop is determined by reversing the filament current and noting the difference in the accelerating voltage for the same results. By means of a spectrograph it can of course be shown that the resonance line is still excited below 10.4 volts.

This beam furnishes a means of getting a relatively high density of positive ions and at the same time colliding electrons having sufficient velocity to excite the ions or produce double ionization. A more complete study of the spectra produced is being carried out.

The auxiliary apparatus necessary to operate the tube can be found in almost every laboratory. They are a 6 volt storage battery, a radio B battery, rheostats, and voltmeter. For most of the work the tube was left connected to the vacuum system. When sealed off, the gas pressure became too high after the filament had been burned a short time. If the metal parts were properly baked out, the tube no doubt could be sealed off permanently.

The writer is indebted to Prof. John T. Tate for many helpful suggestions and for his continued interest.

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Derivation of the Radiation-Law Circumventing the Oscillators and the Appeal to the Classical Theory.—Planck's radiation law is given essentially by the equation $\rho dn = (8\pi n^2 dn/c^3)E$, in which ρ stands for the amount of energy (per unit volume of aether) in radiation of frequencies between n and $n+dn$, and E for the average energy of a set of oscillators of frequency n. In Planck's derivation E is calculated by assuming quantum laws for the oscillators, but the factor in parentheses is taken over from the classical theory of the number of degrees of freedom of a continuous vibrating medium. Bose, in an article bearing the potent approval of Einstein, offers a derivation in which neither the oscillators nor the continuous medium appear. Imagine a cavity of volume V containing a great number of quanta of all frequencies; the state of each quantum is completely described by its frequency n, its 3 coordinates $x\ y\ z$ and its three momentum components $p\ q\ r$, the latter subject to the relation $p^2+q^2+r^2=(hn/c)^2$. In the 3-dimensional space of the variables $p\ q\ r$, the locus of a quantum of frequency n is the sphere of radius hn/c, and the locus of the quanta of frequencies between n and $n+dn$ is the spherical shell of volume $4\pi h^3n^2dn/c^3$. In the 6-dimensional space of all the variables $x\ y\ z\ p\ q\ r$, the volume occupied by the quanta of the specified type is therefore $4\pi Vh^3n^2dn/c^3$, or it is equivalent to $4\pi Vn^2dn/c^3$ cells of volume h^3 apiece. The next step is to calculate the number among these cells which are occupied by zero, one, two, three. . . .quanta apiece, in the most probable state. The frequency range from $n=0$ to $n=\infty$ is divided into intervals dn, and the most probable distribution of quanta of all frequencies is determined in the familiar manner, by calculating virtual variations under the restrictive assumptions that the total energy of the quanta (but not their total number) is constant and the probability of the equilibrium state a maximum. This leads to expressions for the energy and the entropy of the system in terms of universal constants and a quantity β which by working out the equation $dS/dE=1/T$ comes out equal to kT. In the course of the reasoning the factor $4\pi h^3n^2dn/c^3$ which has figured heretofore must be doubled, which is done on the ground that it is demanded by the existence of polarization. Then Planck's radiation law emerges as the final result, obtained without any reference either to oscillators or to classical theory. [Bose, Dacca; ZS. f. Phys. *26*, pp. 178-181; 1924.]

KARL K. DARROW

A NULL-READING ASTATIC MAGNETOMETER OF NOVEL DESIGN

By Richard M. Bozorth

INTRODUCTION

The magnetometers in common use have several disadvantages: (1) they are easily disturbed by extraneous fields due to electrical circuits or to masses of iron which are moved or subjected to changes in temperature, (2) the force exerted at the needle by the specimen is due to the difference in the effects of the induced poles and cannot be greater than that due to one pole, (3) the directing force at the magnetometer must be determined, usually for each position of the needle. These difficulties have been almost entirely eliminated in the instrument described below. The arrangement of two parallel magnets of equal moment and opposite direction, 4 cm apart, forms a system nearly enough astatic for extremely unfavorable laboratory conditions. The specimen is placed so that both of its induced poles produce upon the suspended magnetic system equal torques in the same sense about the axis of suspension. The torques due to the specimen are balanced by those due to a coil of suitable dimensions and position so that the method is a null one. In a similar way the torques due to the magnetizing solenoid surrounding the specimen are annulled by those of a similar solenoid surrounding the balancing coil.

DESCRIPTION OF THE INSTRUMENT

Fig. 1 is a diagram of the magnetometer with its electrical connections. The dimensions of the parts may be chosen to suit various requirements. In an instrument now in use the magnets NS are 4 mm long and 1 mm in diameter. They are, as nearly as possible, of equal magnetic moment, a pair being selected on this basis from a considerable number and then brought closer to equality by filing the stronger. They point horizontally in opposite directions, one 4 cm above the other, being cemented to a light but rigid frame. This frame is suspended by a tungsten wire 0.0013 cm in diameter and 10 cm long. The rotation of this system is observed by aid of a galvanometer mirror mounted at the center of the frame, and is satisfactorily damped by a small vane partially immersed in oil.

The magnetizing solenoids M_1, M_2 are 8 cm long and are placed with axes vertical, on opposite sides of the needle system, and in a plane

perpendicular to the needles so that they are bisected by a horizontal plane halfway between them. These solenoids are alike and are connected in series so that their magnetic moments are equal in magnitude and direction. The purpose of the high resistance shunt R across one of the solenoids is explained below. In one of the magnetizing solenoids is placed the sample S, accurately centered, and in the other is placed the balancing coil B. The whole instrument is hung from the ceiling in a suspension designed to eliminate building vibrations.

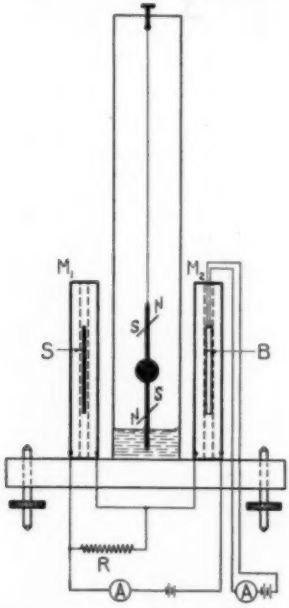

FIG. 1. *Diagram of the magnetometer and its circuits*

In making measurements, the required field is produced in the magnetizing solenoids, and the needle system, rotated by the magnetic field of the sample, is restored to its original position by passing a current through the balancing coil in the proper direction. The magnitude of this current is read on a milliammeter and is proportional to the magnetization of the specimen.

In adjusting the instrument two identically wound balancing coils are used. These are placed one in each magnetizing solenoid and the largest practicable current is passed through the two in series so as to produce

the same polarity. The magnetizing solenoids containing them are then shifted slightly in position until the azimuth of the needle system, as determined by a lamp and scale, is not changed when the current is diminished or even reversed. For greater precision this adjustment is completed by using the leveling screws to produce a slight shift of the needle system with respect to the magnetizing coils. The largest practicable current is now passed through the magnetizing coils, and if necessary, the high resistance shunt R is placed across one of them and adjusted until no rotation of the needle system takes place when the magnetizing current is changed throughout its range. One of the balancing coils is now removed from the circuit, the sample is put in its place and the instrument is ready for use as shown in Fig. 1.

CALCULATION OF THE CONSTANTS

The magnetic field H at the center of the magnetizing solenoid may be calculated in the ordinary way, taking account of the solid angles subtended by the inside and outside layers of the windings. For the usual form of specimen the balancing coil is a long thin solenoid. To find the effect of a single layer of such a solenoid on the magnetometer consider it replaced by a pair of poles of the proper strength and positions. Imagine each turn of wire in the solenoid replaced by its equivalent magnetic shell. The moment per unit area for each such shell is the strength of the current, i; and the total moment, M, of the layer is

$$M = \pi\rho^2 2nli$$

where ρ is the radius of the layer, $2l$ its length and n the number of turns per centimeter. The pair of poles sought must have this same moment in order to have the same magnetic field at a distance. They can also meet the further condition that the total flux they produce is equal to that produced by the layer. The absolute magnitude, μ, of each pole can be found therefore in the following way. The total number of lines of force N produced by this layer is equal to the magnetic field H which it produces at its center, multiplied by the area of its cross-section. N is also equal, by the second condition, to $4\pi\mu$, therefore,

$$\pi\rho^2 H = 4\pi\mu \text{ , or}$$

$$\mu = \frac{H\rho^2}{4}$$

The distance, λ, from the center of the coil to one of the substituted poles, is then one half of M divided by μ, or

$$\lambda = \frac{4\pi nli}{H}$$

The field at the center of the coil is

$$H = 4\pi n i \frac{l}{(l^2+\rho^2)^{\frac{1}{2}}}$$

Eliminating H,

$$\lambda = (l^2+\rho^2)^{\frac{1}{2}} \text{ and}$$

$$\mu = \frac{\pi n i l \rho^2}{(l^2+\rho^2)^{\frac{1}{2}}}, \text{ or}$$

$$\mu = \frac{\pi n i' l \rho^2}{10(l^2+\rho^2)^{\frac{1}{2}}}$$

where i' is the current in amperes.

For a multiple layer solenoid λ may be calculated for each layer and the corresponding length, l_0, for the complete solenoid determined by giving each λ a weight proportional to the cross-sectional area of the corresponding layer. Thus for a solenoid with p layers,

$$l_0 = \frac{\sum_1^p \rho_m^2 (l^2+\rho_m^2)^{\frac{1}{2}}}{\sum_1^p \rho_m^2}$$

where ρ_m is the radius of the m^{th} layer. The equivalent pole strength for the complete solenoid

$$m_0 = \frac{\pi n i' l}{10} \sum_1^p \frac{\rho_m^2}{(l^2+\rho_m^2)^{\frac{1}{2}}}$$

where n, it should be noted, is still the number of turns per cm per layer.

The values of l_0 and m_0 have been calculated for a balancing coil having the following dimensions:

Number of layers	10
Total number of turns	1335
Outside diameter of winding space	0.709 cm
Inside diameter of winding space	0.159 cm
Length of winding space	4.008 cm

It is found that $\rho_1 = 0.0933$, $\rho_2 = 0.1208, \cdots \rho_{10} = 0.3408$; $l = 2.004$, and $n = 33.31$. Thus $l_0 = 2.023$ and $m_0 = 5.528i'$. For a solenoid of these dimensions, then, the equivalent poles may be considered without serious error to be at the centers of its ends.

Under the conditions of measurement the magnetic field produced by the specimen just annuls at the needles the horizontal component of the field due to the solenoid or to its equivalent poles m_0. If the effect of the

sample be approximated in a similar way to that of a pair of poles m_0' at a mutual distance $2l_0'$ it is clear that under the conditions of measurement $m_0' = m_0$ if $l_0' = l_0$. If this be true and if A is the cross-sectional area of a cylindrical sample, the uniformly magnetized cylinder of length $2l_0$ which would be equivalent to the sample in its action upon the needles would have a magnetization $I = m_0/A$. This may be taken as the definition of I which, as in all magnetometric measurements, is some kind of mean value of the magnetization throughout the sample. For the balancing coil described above

$$I = 5.528\, i'/A.$$

PRECISION OF MAGNETOMETRIC MEASUREMENTS

The uncertainty in the value of l_0', and its change with intensity of magnetization,[1] are perhaps the chief sources of error in the determination. By placing the sample at the right distance from the needles, however, the error in I due to uncertainty in the position of the equivalent

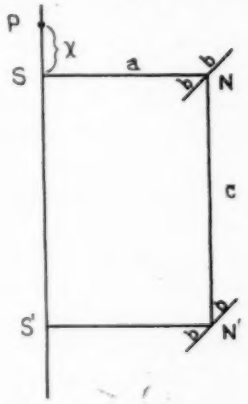

FIG. 2. *Relation of a magnetic pole to the needle system*

poles may be kept comparatively small, and in any case can be determined. As a given magnetic pole is moved along the axis of the sample its torque T upon the needle system passes through a maximum. At this position, of course, the rate of change of T with change of position of the pole is zero and for nearby positions it is small. If the equivalent pole lies in this region its exact position is, therefore, unimportant. In Fig. 2 let N and N' be the centers of the needles, P, S and S' points on

[1] C. G. Lamb, Proc. Phys. Soc. London, *16*, pp. 509-18; 1899; Phil. Mag. *48*, pp. 262-71; 1899.

the axis of the sample (parallel to NN'), and let NS be perpendicular to NN' and to NS. The torque T on the needle system exerted about NN' by a pole placed at P, x cm above S, will be proportional to

$$[x^2+a^2+b^2]^{-3/2}-[(x+c)^2+a^2+b^2]^{-3/2}$$

where $a=NS$, b is the distance from N to the pole of the needle, and $c=NN'$. Maximum torque is obtained for $x=x_0$ given by

$$\left[\frac{x_0}{x_0+c}\right]^2-\left[\frac{x_0^2+a^2+b^2}{(x_0+c)^2+a^2+b^2}\right]^5=0$$

For the apparatus here described $a=2.8$ cm, $b=0.2$ cm, $c=4.0$ cm, and $x_0=0.22$ cm. This value of x_0 is small in comparison with a and c, so that $(dT/dx)_{x=0}$ is small, as it should be to minimize the error in measurement. To larger values of a and b correspond considerably larger values of x_0, for example, if $a=6.3$ and $b=0.7$, $x_0=1.55$. This is too large to make $(dT/dx)_{x=0}$ negligible. Calculation shows that the change in T caused by changing the position of the pole from $x=0$ to $x=0.1$ is less than 1 per cent for the first set of dimensions and about 3 per cent for the second set. Expressed otherwise, the distance between the poles of the sample may change by 5 per cent and cause only 1 per cent error in the determination of I, when the preferred arrangement has been effected.

In magnetometric methods the separation of the equivalent poles of a sample frequently needs to be known for the satisfactory interpretation of the data. This distance varies with the intensity of magnetization. The magnetometer here described permits the measurement of this separation when necessary. A long sample is examined and both ends are cut off repeatedly until the value of T is observed to be a maximum for the chosen value of the impressed field. The separation of the poles for maximum T is calculated in the manner just described, giving the position of the poles in the final condition of the sample.

Knowledge of the demagnetizing factor is frequently important. This subject has been well discussed by Benedicks,[2] who has pointed out the different factors to be used when the method is magnetometric on the one hand, or ballistic on the other.

It has been assumed in the analysis given above that the sample is magnetized only by one magnetizing solenoid. This is not exactly true since the compensating solenoid, the balancing coil and the needles

[2] C. Benedicks, Ann. d. Phys. [4] *6*, pp. 726-40; 1901.

themselves all may produce longitudinal fields within the sample. The effects of magnetizing and balancing currents may easily be calculated in any case where this appears desirable. They are ordinarily negligible. The longitudinal effect of the needles is zero when they are kept in the zero position and they should accordingly be kept so at all times when accurate measurements are being made.

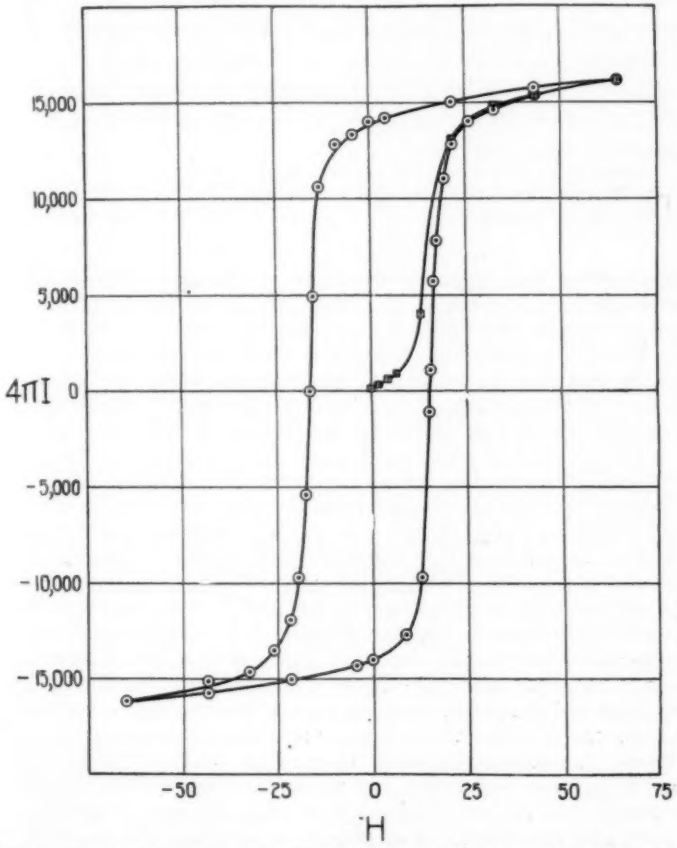

FIG. 3. *Magnetization curve and hysteresis loop for sample of iron wire weighing 3 mg.*

The sensitivity of the instrument is such that the deflection of the spot of light on a scale a meter from the instrument is 1 mm for a change in $4\pi I$ of about 25 gauss, when the sample has a cross-sectional area of 10^{-4} cm.^{2} The corresponding change in the current through the

balancing coil is about 0.03 milliampere. Changes in extraneous fields cause the spot to drift not more than 1 mm from its zero position.

APPLICATIONS

The instrument is especially suitable for measurements with small samples, either in the form of fine wires or thin strips, or as thin deposits on non-magnetic forms of suitable dimensions. Fig. 3 gives for illustration the results obtained with a hard drawn commercial iron wire having a diameter of 0.011 cm and weighing about 3 mg. The length of the wire is here almost 400 times its diameter, so that the demagnetizing factor is very small and has been neglected.

RESEARCH LABORATORIES OF THE
AMERICAN TELEPHONE AND TELEGRAPH COMPANY AND THE
WESTERN ELECTRIC COMPANY, INCORPORATED.
SEPT. 11, 1924.

Scattering and Transformations of Gamma-Rays.—In these experiments the current in an ionization-chamber is measured under three conditions: (*a*) when a beam of gamma-rays traverses it directly; (*b*) when the same beam traverses it after having passed through a metal screen remote from the chamber; (*c*) when the same beam traverses it after passing through the same screen moved into a position where it is almost surrounded by the ionization chamber. In case (*c*) the scattered gamma-rays pass through the ionization chamber, so that the falling off of reading (*c*) as compared with reading (*a*) gives the amount of energy transformed from the gamma-ray form into some other; while in case (*b*) the scattered gamma-rays nearly all evade the ionization chamber so that the falling off of (*b*) compared with (*a*) gives the sum of transformed and scattered energies. Even for very light elements (Al and Mg) reading *c* is less than reading *a*, as if there were a transformation of energy, although it is not commonly supposed that gamma-rays extract internal electrons from such light atoms; the authors argue that this transformation is the transfer of energy from scattered quanta to recoiling electrons, when scattering occurs in the Compton fashion. They attempt to compare the observed amount of energy transformation with theoretical values derived from the newer theories of scattering, but the wave-length of the gamma-rays is evidently not known well enough to make the comparison valuable. In analyzing the absorption of gamma-rays by heavier elements, they assign a portion of it to this mechanism by extrapolations which require further test. [E. A. Owen, N. Fleming and W. E. Fage, National Physical Laboratory; Proc. Phys. Soc. Lond. *36*, pp. 355-366; 1924.]

KARL K. DARROW

TWO MODIFICATIONS OF THE SIMPLE DRUM TYPE POTENTIOMETER AND A DESIGN FOR A DOUBLE POTENTIOMETER

By A. G. Worthing and W. E. Forsythe

CONVERSION TO A LIMITED DOUBLE POTENTIOMETER

In a study of the "effects of strong electrostatic fields on the vaporization of tungsten" by one of the writers,[1] it was found necessary to follow closely the voltage variation in a tungsten filament operating at constant current. To do this satisfactorily and to avoid using two potentiometers or incurring the expense of a new double potentiometer, a change in the ordinary instrument was required. A modification was worked out whereby the shift from a voltage to a current setting was made by merely throwing a special switch.

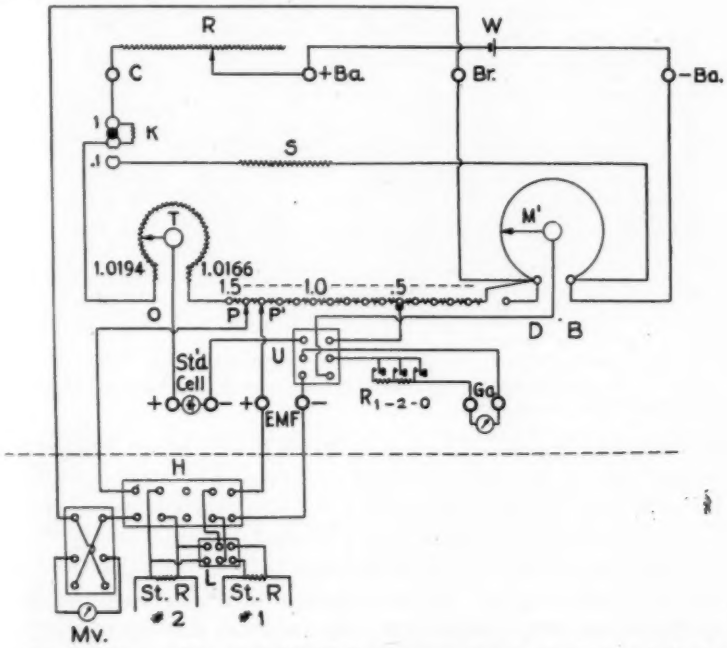

FIG. 1. *Diagram (above dashed line) showing connections in the Leeds and Northrup type K potentiometer. Diagram (taken as a whole) showing conversion to a double potentiometer with one branch a deflection instrument.*

[1] Phys. Rev. *17*, p. 419; 1921.

Fig. 1 shows a diagram of the Leeds & Northrup type *K* potentiometer. Fig. 2 shows a diagram with the modification introduced. Fig. 3 shows a photograph of the actual instrument with the extra rocker switch, *E*, the extra pair of terminals, *X*, and the double dial handle, *Z*, giving the two contacts, *P* and *P'*.

In applying the modified potentiometer to the problem for which it was designed, connections for current measurements were made from a variable standard resistance, varying in five steps from 0 to 5 ohms, to emf #2 terminals of Fig. 2. The dial contact *P* was set to correspond to

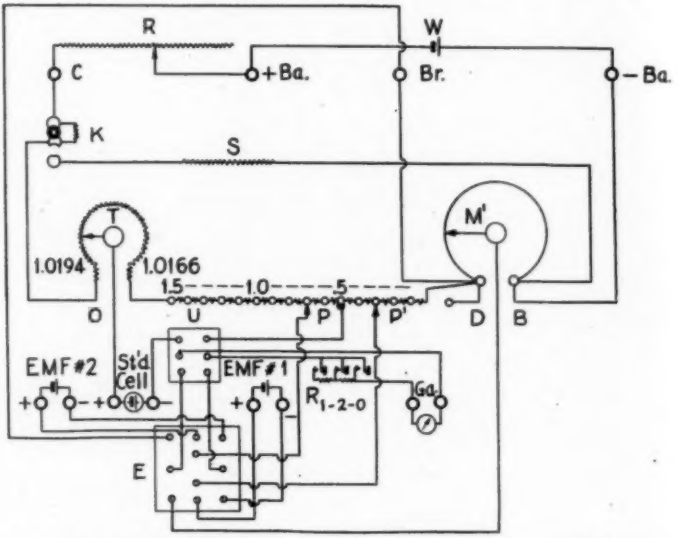

FIG. 2. *Diagram showing the conversion of the Leeds and Northrup type K potentiometer into a limited double potentiometer.*

the current to be used. The rocker switch *E* was thrown forward and the resistance in the outside circuit, as indicated by a zero galvanometer deflection, was adjusted until the desired current was obtained. The rocker switch was then thrown backward; the dial contact *P'* and the drum contact *M'* were set in the usual manner to give the potential reading. Following this, the only changes in setting were the small changes in the drum contact, *M'*, that came as a result of the slow vaporization of the filament or of the changed electrostatic field. Shifting from current setting to potential setting necessitated merely the throwing of the rocker switch. There resulted a great saving in

time and complete freedom from the annoyance due to rendering the galvanometer temporarily useless by a wrong setting.

This modified instrument has an unfavorable limitation. One of the settings can be modified by definite steps only. Wherever it is desired to keep close track of two potentials or currents, one of which may be varied by steps only, corresponding for instance to 120 volts, 110 volts,

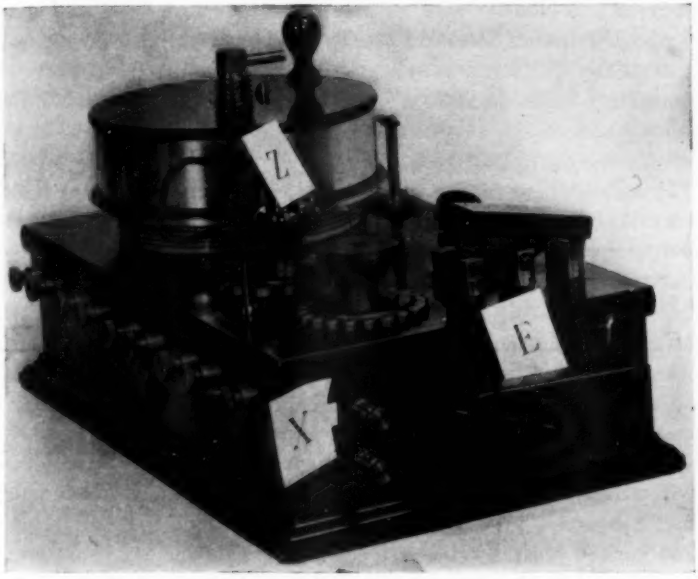

FIG. 3. *Photograph showing a Leeds and Northrup type K potentiometer that has been converted into a limited double potentiometer.*

100 volts, etc., this device will be found very convenient. For cases, however, where the two settings are to be separately adjustable to all values, it is necessary to construct a double potentiometer if one wishes in a single instrument the rapidity of action and freedom from annoyance which the above described modification has yielded in its limited field.

CONVERSION TO A DOUBLE POTENTIOMETER WITH ONE BRANCH A DEFLECTION INSTRUMENT

In measuring pyrometer currents for the disappearing filament pyrometer, an ordinary ammeter is not sufficiently sensitive for some

work; at the same time the standard potentiometer is too slow in operation for regular use, particularly so if the same potentiometer is to be used in controlling the heating current of the source (background) studied. A standard deflection potentiometer will partially overcome these difficulties. But in its use some difficulty is experienced due to the necessity of shifting both the dial and an external switch when changing from the pyrometer current to the background current. An arrangement which the authors' have used for many years and is here described,[2] however, does away with trouble resulting from failure to coordinate properly the switch and dial adjustments, gives the quick response needed in measuring the pyrometer currents, and retains the accuracy and ease of the standard potentiometer without dial adjustment for the control of the background current.

The arrangement of apparatus is shown in Fig. 1. Except for the connections from one part to the other, that portion above the dotted line represents the standard instrument, and that below the dotted line the additions desirable for this conversion. *H* is a special double-throw switch (theoretically two double-pole, single-throw switches with handles properly joined are sufficient); *St. R.* #1, the standard resistance in the background current circuit; *St. R.* #2, that in the pyrometer lamp circuit. At *Mv* a low range millivoltmeter (0 to 50 millivolts, 10 ohms) or a low sensitivity portable galvanometer is very suitable. The galvanometer switch in the potentiometer may be kept closed. *L* is a switch for use in measuring the pyrometer current on the potentiometer directly.

For work in optical pyrometry the regular dial and the drum are set to correspond to the desired current for heating the background and adjustments are made externally for obtaining and maintaining that current in the customary manner. For this, switches *H* and *L* must be thrown to the right. But for the measurement of a series of pyrometer currents, I_p, of about the same magnitude, a different procedure is followed. *H* is thrown to the left, and the position of the *P* contact on the dial[3] which yields the least deflection for the millivoltmeter, *Mv*, is found (once for the series of readings). The deflections are then read and recorded. In effect a part of the current is read on the dial of the potentiometer while the remainder is read on the millivoltmeter, *Mv*.

[2] Pyrometer Symposium, A.I.M.M.E. p. 148; 1920.

[3] This may also be simply obtained by means of a metal plug which fits the holes in the regular dial contacts.

For instance in measuring a current of 0.05345 amp., a 10 ohm standard would be used as St. R. #2; and the P dial reading will be 0.5 (0.05 amp.) while the Mv reading will be, say, 302 for a particular arrangement. It is to be noted that meanwhile the adjustment of the potentiometer for measuring the background current has not been disturbed. All that is necessary in checking this current is to reverse the switch H. Later in case the Mv circuit has not been adjusted to make Mv read directly, the part of the mean I_p current which the mean of a number of individual readings represent may be determined directly. Except for very accurate work, this last step may often be dispensed with, for it usually is satisfactory to use a given factor (one for each setting of the dial) once determined to transfer the mean of the Mv readings into actual current values. Thus for the case illustrated above the factor is 345/302 or 1.147.

An illustration of the usefulness of this arrangement of apparatus is shown by the following data obtained in some work on the reflectivity

Back ground Current	Conditions	Mv Readings				I_p
		Bright	Dark	Average	Mean	
2.1 amp.	Direct	291 96 99	323 27 20	307 11 09	.05+ 308	.05352 amp.
2.1 amp.	Reflected	209 07 00 00	153 62 47 45	181 84 73 72	.05− 177	.04798 amp.

of gold. Bright and dark readings refer to observations obtained when the pyrometer filament is made to just disappear after having been brighter or darker than the background. It is to be noted that a unit in the last place of the millivoltmeter readings corresponds in this case to about 1/4500 part of the whole current. With a more sensitive millivoltmeter the sensitivity of this arrangement for measuring current may be increased.

For use in this work a millivoltmeter with the zero shifted slightly to one side possesses some added advantages which are obvious when the Mv deflections are likely to include in one series both positive and negative values.

To have made the readings tabulated above on an ordinary potentiometer in the usual manner, considering that the potentiometer was also used to control the background current, would have at least doubled the actual time spent in obtaining the data.

DESIGN OF A DOUBLE POTENTIOMETER

The modification of the Leeds & Northrup potentiometer described in the first section of this paper can be easily adapted to a double potentiometer which is fairly simple in construction and is not so limited in its use. The adaptation consists essentially in adding a drum slide resistance similar to the one already incorporated in the instrument and shifting the fixed contact at *Br* to the adjustable contact of the added drum. This drum slide resistance may be placed conveniently (1) in parallel with the drum already a part of the instrument, (2) in series with that drum and the dial in place of the 0 to 1 dial resistance, or (3) in series with the dial at the end opposite from the present drum. If in the first location, the two drum slide resistances will preferably be both made equal to double that of the present drum. If in the second location, the resistance of the added drum must correspond exactly to that of a unit of the dial; further it will be desirable to construct the added dial contact in such a way that its indicator points to one post back of the one at which contact is made. If in the third location, it is necessary to incorporate the extra resistance for the standard cell adjustment as a part of one of the dial units and to introduce a second dial scale which shall read in the reverse direction. In the finished instrument, whichever method is used, it is desirable that the dial scales be separated and that one dial scale and connected drum be placed on the left and that the other dial scale and drum be placed on the right.

NELA RESEARCH LABORATORY,
NATIONAL LAMP WORKS,
CLEVELAND, OHIO.
JUNE, 1924.

A MICRO-FURNACE FOR HIGH MAGNIFICATION

By H. S. Roberts and Taisia Stadnichenko

The microscopic study of coals and carbonaceous shales has yielded a large volume of information regarding the botany of the plants contributing to the formation of these sediments. Chemical methods and the use of solvents as a means for identifying the various constituent parts as chemical individuals have proved inconclusive. It was therefore decided to obtain further evidence by heating thin sections of the coal or shale in an inert atmosphere; to observe, optically, the melting and volatilization of the constituents and simultaneously to measure the temperatures at which these phenomena take place.[1] Data obtained in this way have in many cases been found sufficient for identification of particular constituents and may be expected to be valuable in the development of efficient methods of extracting energy and useful products, as well as information, from these fuels.

A small resistance furnace of the cylindrical type was constructed for the purpose and gave promising results; but was found inadequate for the examination of the smaller fossil debris in the agglomerate, many of the spore exines, lumps of resin, etc., being less than 0.005 mm in diameter. In order to obtain sufficient useful magnification it was accordingly found necessary to provide a furnace in which the sections could be studied with a 16 mm objective of large aperture. On account of the short working distance of this objective the conventional, cylindrical tube type of furnace would have had to be made inconveniently short, especially so since the objective must be kept reasonably cool; furthermore, measurement of the temperature of the specimen or charge in such a furnace would be difficult and uncertain. It was therefore decided to place the charge between two strips of silica glass which could be heated by a broad electric heater of nichrome ribbon bent back on itself so as to inclose the strips. In this arrangement holes must of course be cut in the heater in order to see through it, and we depend on the thermal conductivity of the glass strips to insure a sufficiently uniform temperature over the resulting gap in an otherwise nearly continuous heater. In order to prevent oxidation of the specimen the furnace is closed and kept free from air by passing a current of helium through it.

[1] This investigation is being conducted by the junior author at Vassar College, Poughkeepsie, New York.

The general appearance of the completed furnace is shown in the photograph, Fig. 1, while the details of its construction are given in Fig. 2. The heater *H* is made of nichrome ribbon 5 mils (0.127 mm) thick and 1/2 inch (12.7 mm) wide. The ends of the ribbon are bent outward and secured to the body of the furnace by screws on either side of the opening *O*. Electrical connection with the heater is made through the lower plate *B* of the furnace housing and through a terminal block *T* which is secured to the base but insulated from it with mica.

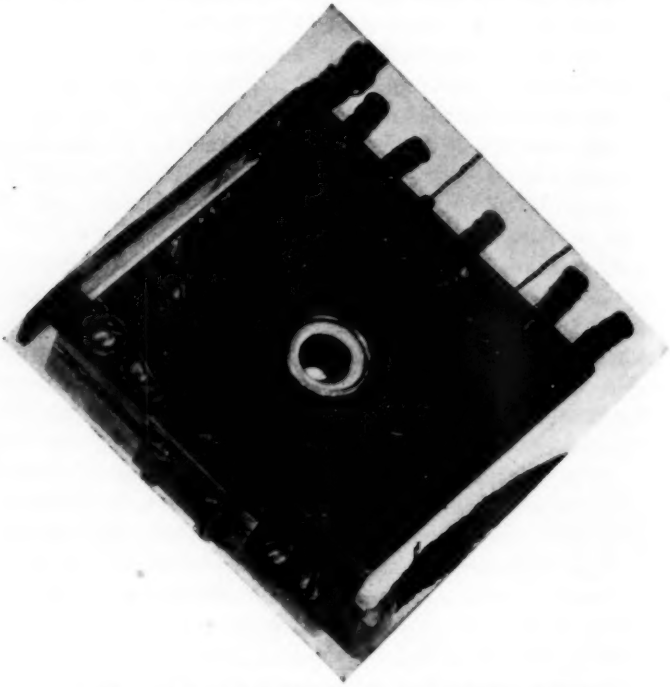

FIG. 1. *Photograph of micro-furnace* (About 1.5 natural size.)

The spaces above and below the heater are occupied by strips of mica which were heated for some hours at about 950°; this treatment drives off water and causes the mica to swell to several times its original thickness, making it a fairly good thermal insulator with sufficient mechanical strength to keep the heater centered. Current is brought to the furnace by stranded copper wires soldered to the copper lugs *L*. The temperature is measured by the thermocouple *C* whose junction

is located at J in a notch in the porcelain block P. These various parts are enclosed in a rather massive brass housing which is divided horizontally to facilitate assembling. Windows W of thin silica glass are provided opposite the holes in the heater and a water duct D in each half carries a stream of water to keep the housing cool.

When the furnace is filled with an atmosphere of helium the hatere requires a current of about 40 amperes to reach 800°C. This current is supplied by an 11 volt sign-lighting transformer and is controlled by a rheostat and ammeter in series with the primary winding of the transformer.

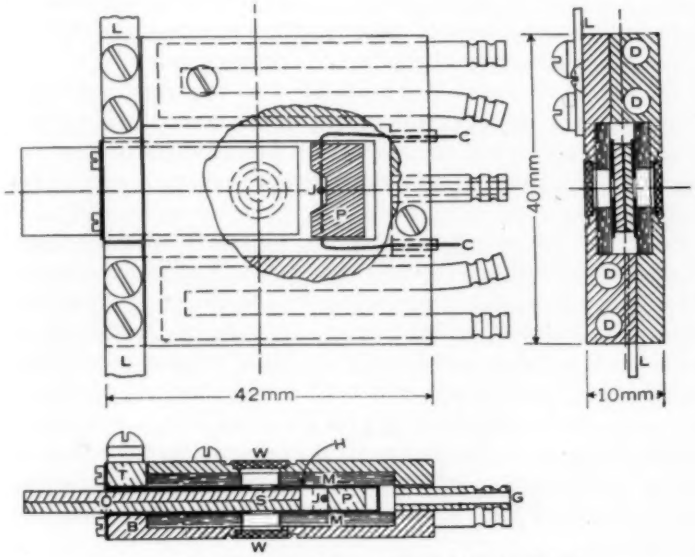

FIG. 2. *Details of micro-furnace* (About 1.2 natural size.)

The specimen to be investigated is placed between the glass strips S, which may be moved about under the microscope without moving the whole furnace. In the particular investigation for which this furnace was made, a continuous stream of helium enters the furnace cavity through G and leaves by the opening O through which the slides are introduced. Since the spaces above and below the heater are filled with mica, the flow of gas is confined chiefly to the sides, where it has least effect on the temperature of the charge. However, owing to the fact that the junction of the thermocouple is some millimeters from

the charge, it was found advisable to choose some rate of flow for the gas that would in all cases be sufficient to prevent oxidation of the material being investigated, and to maintain this rate within a few per cent during calibration of the thermocouple and whenever temperature measurements were being made. For this purpose a simple flow meter located in the gas line gives a continuous and sufficiently accurate indication of the rate.

The calibration of the thermocouple is carried out by noting its reading when a standard substance, such as a pure salt or a pure metal, substituted for the usual charge, is held at its melting point. This is really a calibration of the thermocouple and furnace together, for it automatically takes care of whatever difference there may be between the temperatures of the charge and of the junction.

In order to determine how much effect on the temperature readings might be expected from accidental variations in the gas flow, powdered potassium dichromate was substituted for the usual charge and the reading of the thermocouple noted when the furnace was held at the melting point of the dichromate (397.5°). This was carried out three times in currents of helium flowing 27, 64, and 108 cc per minute; the thermocouple readings were 16.6, 17.3 and 17.5 millivolts respectively. The change in apparent temperature is going from 64 to 108 cc/m in amounts to about 4°, so that a change of 10 per cent in the rate of flow between these values could hardly introduce an error greater than 1°. In this experiment, as well as in another where sodium chloride (melting point 800°) was substituted for the dichromate, it was found that while melting did not begin simultaneously over the whole field, it was not at all difficult to hold the temperature for about 30 seconds at such a point that there would be partly melted material in all parts of the field.

In conclusion the authors desire to express their indebtedness to Mr. Charles J. Ksanda of the Geophysical Laboratory, who not only built the furnace, but who made many valuable contributions to its form and to the method of using it.

GEOPHYSICAL LABORATORY,
WASHINGTON, D. C. (H.S.R.),
VASSAR COLLEGE,
POUGHKEEPSIE, NEW YORK. (T.S.)

A SUSPENSION FOR SUPPORTING DELICATE INSTRUMENTS

By A. L. Johnsrud

The various types of disturbances which render the use of delicate instruments in the laboratories of to-day in many cases difficult are effectively eliminated by the suspension herewith described. The two special features which make it differ from suspensions commonly used heretofore are: (1) The very effective elimination of vertical vibrations by means of a system of tape wound coil springs, and (2) The possibility of adjusting the moving system of the instrument with minimum disturbance.

In the figure, t_1 t_2 t_3 are three triangles made of iron or brass strips. Hooked into them at the corners are S-hooks, which are connected to the coil springs. These springs measure about 15″ before they are tensed and about 18″ to 19″ afterwards. For heavy suspensions and instruments, two springs in parallel are used in each position. It has been found that common screen-door springs do very well.

Suspended from the bottom triangle by means of turnbuckles *aaa* and extension rods or wires, is a frame consisting of three vertical rods r_1 r_2 r_3 held firmly at the ends with round plates. Adjustable in height on these rods are three lead weights w_1 w_2 w_3 whose masses are determined by the maximum instrument mass likely to be used and the height of the support for the moving system above the base. These masses have to be great enough to make the center of oscillation of the frame and instrument coincide with the point of support of the moving system. At the same time, the three clamps C_1 C_2 C_3 (C_2 is behind the instrument) are at such a height on the rods that the plane of the three points of support of the frame contains the point of support of the moving system. This prevents the turning or twisting impulse of adjusting the instrument from disturbing the moving system more than in a secondary degree, so that, after an adjustment, the instrument is almost immediately ready for further readings.

In the figure, P is a lead slab adding mass to the lower part of the frame. A moving magnet type galvanometer is shown in place on the suspension. It was especially for this instrument that the refinements of this suspension proved valuable because, with its moving system of only a fraction of a gram of mass supported by a .0003″ quartz fiber, a

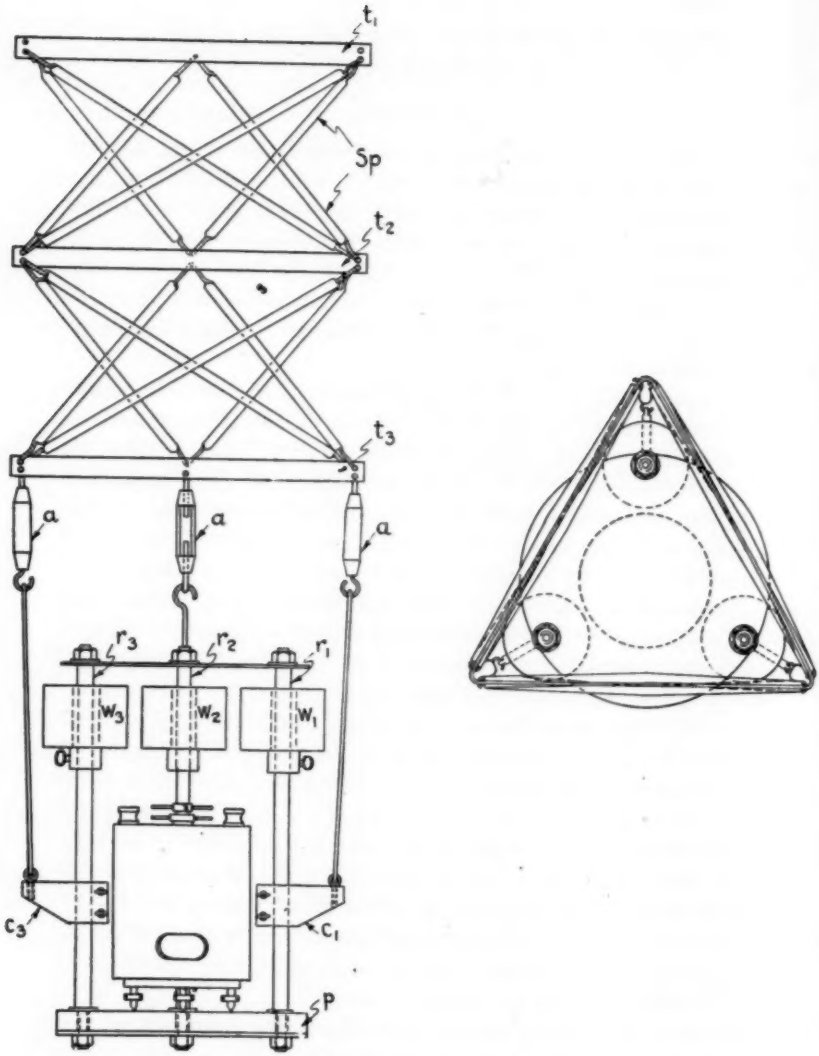

FIG. 1. *Suspension for delicate instruments*

current sensitivity of 2.8×10^{-11} amp. was attained by careful adjustments even while trucks and street cars produced strong mechanical and electrical disturbances.

The springs, *sp*, are wound tightly with friction tape over the entire length, each turn lapping the previous one by about half the width to form two layers. This is done after the suspension is hung but before the instrument is put in place, so as to tense the tape and make it snug around the coils of the spring.

It is essential that the top triangle t_1 be held firmly clamped so as not to be allowed to turn or tilt with respect to the building structure. If the suspension is allowed to swing ever so little, the damping effect of the tape is rendered ineffective. Also, it is essential that the entire length of each spring be completely covered with tape. As many sections of springs as is convenient, one above the other, can be used, though two have been found amply effective for the most sensitive instruments. In one case, where it was necessary to mount a quadrant electrometer in an iron box, a miniature suspension, 20 inches high over all, including one section of springs, was used. It was found to be satisfactory, although disturbances due to heavy trucks on the adjoining street were just becoming discernible.

This suspension was developed some years ago through the efforts of Mr. H. C. Harrison and Mr. J. P. Maxfield, and has since been adapted for use throughout our laboratories in a variety of ways.

RESEARCH LABORATORIES OF THE
AMERICAN TELEPHONE AND TELEGRAPH COMPANY AND THE
WESTERN ELECTRIC COMPANY, INCORPORATED
DECEMBER 9, 1924.

Highly Polarized Infrared Light Emitted Obliquely from an Incandescent Platinum Surface.—It has often been shown by experiment, in concordance with theory, that the light emitted obliquely from an incandescent polished surface of Pt is partially polarized; the component E_p having its electric vector in the plane of incidence predominates over the other, E_s. As the index of refraction of Pt increases with λ it is foreseen that this polarization should be much more nearly complete in the far infrared than in the visible. This was tested by removing from the emitted light all the wave-lengths except that corresponding to the "Reststrahlen" of calcite, 6.76μ, and measuring the ratio of intensities of E_s and E_p. The prediction was verified; E_s/E_p was found to be only 0.28 in the light emitted at 60° to the normal, and only .008 at 87° (as contrasted with 0.05 at 86° with red light). A comparison of the data with values calculated by assuming $n=23.14$, $k=1$ (an extrapolation from observed values, not sustained

by measurements) gives a good qualitative agreement, but the calculated values of E_s/E_p are all too small. Measurements of E_p at angles from 85° to 90° show that it passes through a maximum at about 88°; measurements of E_s between 60° and 90° show that it decreases almost linearly with increasing angle. This is proposed as a method for generating plane polarized infrared light. [M. Czerny, Berlin; ZS. f. Phys. *26*, pp. 182-187; 1924.]

KARL K. DARROW

Artificial Disintegration of the Elements.—In previous experiments designed to detect H- particles expelled from the nuclei of atoms under bombardment by α-rays, it has been necessary to confine the observations to the particles emerging from the bombarded substance with ranges greater than 30 cm, for any with lesser range might originate from hydrogen atoms occluded in the substance. One can, however, be confident that particles emerging at 90° to the bombarding beam do not come from hydrogen atoms; the only particles to be expected in that direction are scattered alpha-particles having a range no greater (and, if the scattering atoms are light, distinctly lower) than the range of the oncoming alpha-particles, and particles coming from disrupted nuclei. Thus it was possible to test whether Li, Be and C nuclei are disrupted in such a way as to give particles of a range exceeding 2.6 cm; the answer is negative for Li, dubious for Be and C. For other atoms it was possible to test for particles of greater range than 7 cm; and *all* the elements from oxygen to potassium inclusive, as well as boron and nitrogen, yielded such particles. The ranges of the particles from the even-numbered elements are, however, consistently smaller than those of the particles from the odd-numbered elements. These are maximum ranges; the *minimum* range for Al and S was likewise determined and found to correspond to an accelerating p.d. of the order of 3,000,000 volts. Suppose that the force between nucleus and emitted particle is the resultant of an inverse-square repulsion and an attraction varying as some power of $1/r$ higher than the second, for example the fourth; this 3,000,000 volts would then be not less than the p.d. between exterior space and the spherical locus where these forces balance; assuming it equal to the said p.d., the distance from the nucleus to this locus of zero force can be evaluated. The plausible value $6 \cdot 10^{-13}$ cm is so obtained, and satisfactory values are likewise calculated for the fraction out of a large number of alpha-particles fired at a stratum of atoms which will penetrate as far as the locus of zero force, which are the only ones that can disintegrate the nucleus. Rutherford thinks that the particles observed by Kirsch and Petterson (reviewed in this Journal, *9*, p. 350) and supposed by them to come from disrupted nuclei of Be, Mg, and Si, originate in the radioactive source. [E. Rutherford and J. Chadwick: Proc. Phys. Soc. Lond. *36*, pp. 417-422; 1924.]

KARL K. DARROW

NEW RULING FOR HAEMACYTOMETER CHAMBERS*

LEWIS V. JUDSON

Haemacytometer chambers are used for counting the corpuscles of the blood and consists of a glass slide having a polished strip, bearing special rulings, which is 0.1 mm below the surfaces on either side that support the cover glass. In the United States the use of the Neubauer ruling shown in Fig. 1 has been rather general for these instruments. Its use has not been entirely satisfactory because of the liability of the person using the chamber to make errors on account of the confusing nature of the lines.

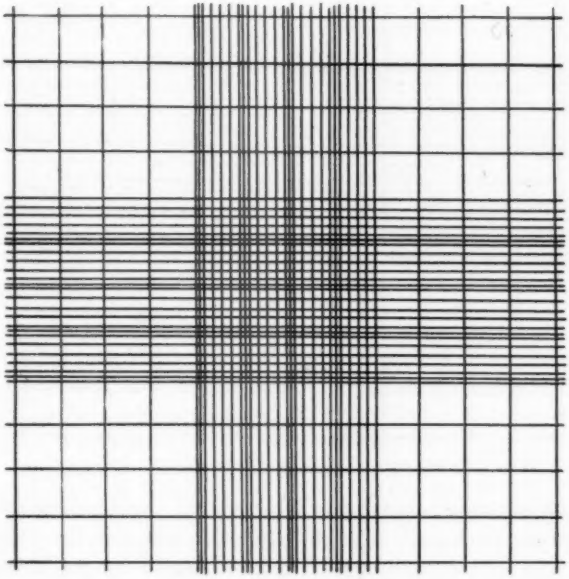

FIG. 1. *Original Neubauer Ruling*

A new type of ruling shown in Fig. 2 has been submitted to the Bureau of Standards for inspection and test, and appears to possess an advantage to the physician using the instrument in the diagnosis of disease because of the greater certainty with which it can be read. Not only does the new ruling more clearly define the boundary lines of the

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subdivision of the millimeter square into its principal parts but also it permits a standardization of this ruling with a precision which is certainly equal to that obtained with the old type. Certain features of it are novel and the idea may be of service in other lines of work.

This general idea may be applicable in other lines of work and it is proposed to determine whether it may contribute to solving some of the problems of precision standards of length in which the character of the line always plays an important part.

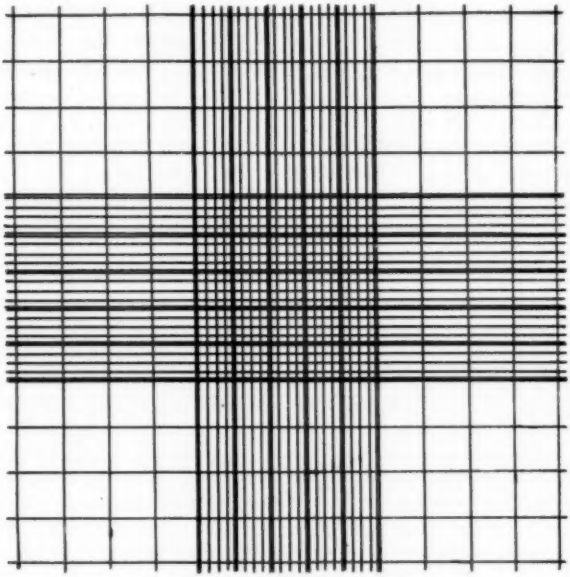

FIG. 2. *Improved Neubauer Ruling*

As shown in the accompanying illustrations, the essential feature of the new ruling is the use of double lines to mark out the twenty-five principal squares which altogether form a square one millimeter on a side in the central part of the whole ruling. Where the double line occurs the center of the transparent portion between the two opaque lines is the boundary line of the squares 0.2 mm on a side, these squares being further subdivided into sixteen squares by the usual single lines. In the case of one of these chambers the measurements made in the laboratory showed that the two lines were each 0.0025 mm wide with a clear space 0.002 mm wide between them. The side of each of the smallest squares is 0.050 mm.

The ruling has distinct advantages over the ordinary Neubauer ruling because of its being less complex and less liable to give mistakes in the counting of the corpuscles. The rulings may be made so that the accuracy of standardization is high and the method may prove to be applicable to other sorts of ruling.

BUREAU OF STANDARDS,
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Fluorescence Bands Produced by Irradiating Iodine Vapor with λ1854.—The chief result of this work is that Oldenberg establishes the existence of fluorescence bands of iodine which do not disappear, but may even become brighter (although they suffer a transformation in appearance) when the iodine vapor is diluted by an enormous excess of a different gas. Notably this is the case with the diffuse bands between 2000A and 4800A, which are excited by λ1854 (or adjacent wave lengths) in pure iodine vapor of the density corresponding to equilibrium with solid iodine at room temperature. As nitrogen is mixed in increasing proportions into this vapor, the bands near 4800A become brighter and more diffuse, and even at 760 mm of nitrogen remain visible. Furthermore, a band with its long wave end at 3460, invisible when the iodine is pure, appears when some nitrogen is added and remains visible and even brilliant when the nitrogen has a pressure of 760 mm and greater; it also develops a fine structure when the pressure of nitrogen is great, and is brought out by other gases too, although not equally well. Here then are instances in which the addition of foreign gases to the fluorescing gas does not solely divert into other channels energy wh ch would otherwise be radiated in fluorescence. Oldenberg considers that the band ending at λ3460 is due to recombinations of pairs of charged iodine atoms, one positively and the other negatively charged. This differs from Gerlach's and Gromann's interpretation (cf. this Journal, *9*, pp. 349-350) and has not so striking a quantitative agreement as theirs to support it; much of the article is taken up with a comparison of the two ideas. It would be advantageous if the critical potentials of I_2 and I were better known. Oldenberg likewise observes a band near λ5100 excited only from mixtures of iodine and hydrogen. [O. Oldenberg, Gottingen; ZS, f. Phys. *25*, pp. 136-159; 1924.]

KARL K. DARROW

Method of Repairing Broken off Lead-in Wires.—In high vacuum work where are being used a number of lead-in wires, extending out in more or less of a temporary fashion, it is not unusual for one of these wires to break off at the surface of the glass. Repairing such a break is difficult and if the wire is to carry a large current it usually necessitates making a new tube. A temporary repair may be made as follows.

By means of a small glass rod the little bit of broken off lead-in left exposed is moistened with nitric acid. This tip is then amalgamated by placing a small drop of mercury on it. The tip of another wire, to take the place of the one broken off, is dipped into nitric acid and also amalgamated. Upon sticking the amalgamated tip of the repair wire into the drop of mercury hanging to the broken off lead-in a perfect connection is obtained and one that will carry as large a current as before the break. Of course this connection has no mechanical strength but that is unimportant since the strong repair wire can always be fastened rigidly to the tube or some part of the set-up, making it unnecessary for the joint to have mechanical strength.

This method of repair gives satisfaction over quite a long period of usage and is easily adapted to the worst breaks.

D. A. WELLS, University of Cincinnati, Cincinnati, Ohio

Ionizing Potential of Iron.—From an analysis of the previously known multiplets in the spectrum of iron and of one more which they discern near λ3700, Gieseler and Grotrian identify three quintuple levels corresponding (at least in notation) to the *3d*, *4d* and *5d* levels of simpler spectra; the level $3d_4$ is the normal level occupied by the loosest electron. Forming the levels $3d_4$, $4d_4$ and $5d_4$ into a series, and extrapolating to the limit of this series by a formula of the Ritz type in which the two numerical constants are assigned values which fit the three observed levels, the authors calculate 8.15 volts for the ionizing potential of Fe. [H. Gieseler and W. Grotrian, Potsdam; ZS. f. Phys. *25*, pp. 165-172; 1924.]

KARL K. DARROW

A SIMPLE EXPERIMENTAL PROOF OF OHM'S LAW FOR LABORATORY USE

By N. E. Wheeler

For several years we have been using, with a good degree of satisfaction, the following simple arrangement of apparatus—which was devised by the writer and first used at McGill University—for the verification of Ohm's law in the electrical laboratory work of our elementary students. This description is published in the hope that the method will be found more satisfactory and more suitable for usage in elementary laboratories than the stock experiments usually adopted for this purpose.

On looking up the treatment of this experiment in ten well-known manuals or experimental text-books, chosen more or less at random, it appears,—

(*a*) that four attempt no proof of Ohm's law whatever;

(*b*) that one makes use of a single storage cell, a resistance box, a tangent galvanometer, and a reversing switch;

(*c*) that one makes use of one cell, then two cells in series, and so on; and

(*d*) that, of the other four, two make use of voltmeters, one of a calorimeter, and one of a potentiometer in the measurement of the potential drop, E volts, across a long wire or resistance coil, while the current, I amperes, is measured by means of an ammeter in three cases and a tangent galvanometer in the fourth.

Obvious criticisms of the method of (*b*) are that use is made of a resistance box constructed on the assumption that Ohm's law is true, thus rendering the experiment no real proof of the law, and further that, since only one value of E is used, the experiment fails to prove that the exponent of E has not some other value than unity.

An objection to the method of (*c*), since Ohm's law applies to a given *definite* circuit, is the introduction during the course of the experiment of additional resistance into the circuit by inserting a second cell in series with the first, and so on.

Of the methods of (*d*) it may be said that the use of the potentiometer in the measurement of E seems somewhat involved for the elementary student, that the use of voltmeters might raise the question as to whether the voltmeters were calibrated by a method independent of

Ohm's law, and that the measurement of E by means of a calorimeter method is likely to be lacking in precision as well as in simplicity.

The arrangement of apparatus used is shown in the accompanying diagram and consists of five similar storage cells of emf's E_1, E_2, . . . , E_5 connected in series through the commutators C_1, C_2, . . . , C_5 (mounted on a wooden base AB) to a constant length or coil of wire R (of resistance about 100 to 300 ohms depending on the galvanometer used), a reversing switch S, and a tangent galvanometer G.

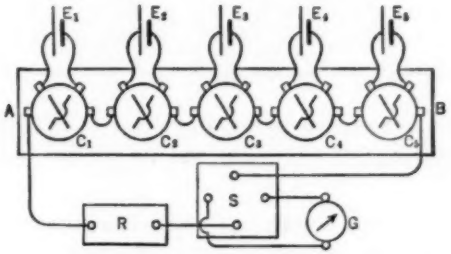

FIG. 1. *Arrangement of apparatus for proof of Ohm's law.*

By means of the tangent galvanometer the current, I amperes, in the circuit can be measured by a method which does not involve the assumption of Ohm's law, using the usual formula,

$$I = \frac{10\,Hr}{2\pi n} \tan\theta = K \tan\theta,$$

where θ is the angular deflection of the needle and K is a constant for the galvanometer in any given position.

Suppose the emf's of all the cells are exactly the same and each equal to E volts. Then when one cell, say number one, is reversed the equivalent emf in the circuit becomes $3E$; while if two cells are reversed the equivalent emf becomes E. In this way, since all five cells are kept in series throughout the experiment, we avoid alterations in the resistance of the circuit produced by inserting or removing cells during the course of the experiment.

In practice, E_1, E_2, . . . , E_5 will, in general, differ slightly one from another. Call their average value E_a. Then before reversing any of the commutators the equivalent emf in the circuit is $5\,E_a$.

Next consider the case where one cell is reversed at a time, first

number one, than number two, and so on. The equivalent emf in the circuit in the several cases respectively is expressible as follows:

$$5E_a - 2E_1,$$
$$5E_a - 2E_2,$$
$$5E_a - 2E_3,$$
$$5E_a - 2E_4,$$
$$5E_a - 2E_5.$$

Adding and dividing by 5, we obtain the average value of the equivalent emf in the circuit which is $5E_a - 2E_a$, or $3E_a$.

If the five possible groups of two consecutive cells taken in cyclic order are similarly reversed, the equivalent emf in the circuit in the several cases respectively is as follows:

$$5E_a - 2E_1 - 2E_2,$$
$$5E_a - 2E_2 - 2E_3,$$
$$5E_a - 2E_3 - 2E_4,$$
$$5E_a - 2E_4 - 2E_5,$$
$$5E_a - 2E_5 - 2E_1.$$

The average value of the equivalent emf in the circuit in this case is $5E_a - 2E_a - 2E_a$, or E_a.

It is well to begin with a galvanometer deflection of 65° or 70°, when the equivalent emf is $5E_a$, so that the deflections may not be too small when the equivalent emf is reduced to E_a, since the effect of small errors in reading the angular deflections has a much greater effect on the values of the tangents of angles between 0° and 20° or between 70° and 90° than of angles near 45°.

It is our practice to direct the student to read both ends of the tangent galvanometer needle and then reverse the switch S and read both ends of the needle again, thus making four readings in each set. Five such sets of four readings each are taken before reversing any of the cells, the mean of these giving the value of θ corresponding to an equivalent emf of $5E_a$.

Then a set of four readings of θ is taken with cell number one reversed; then similar sets with each of cells two, three, four, and five reversed in turn. The mean of these twenty readings is the value of θ corresponding to an equivalent emf of $3E_a$.

Finally similar sets of readings are taken with each of the five possible groups, of two consecutive cells taken in cyclic order, reversed. The mean of these twenty readings is the value of θ corresponding to an applied emf of E_a.

If a graph is plotted with average values of E, i.e., $1E_a$, $3E_a$, etc. as abscissae and of tan θ as ordinates and if, within the limits of experimental error, these points fall on a straight line passing through the origin, then Ohm's law or the statement that *the current flowing in any given circuit is proportional to the emf producing it* is verified within corresponding limits.

A typical set of results is given in the following table:

Average Value of E	Average Value of θ	Tan θ	$\frac{E_a}{E}\tan\theta$	Deviation from Mean
$5E_a$	64.25°	2.073	0.415	−0.003
$3E_a$	51.76°	1.269	0.423	+0.005
E_a	22.64°	0.417	0.417	−0.001
0	0	0	——	——

If desired, an additional point could be obtained by the use of seven instead of five cells; and the experiment could be repeated with a different resistance wire or coil in the circuit to further indicate that the law established for the above circuit holds in general, but this hardly seems necessary.

Obviously the resistance wire or coil used should be such that its temperature coefficient of resistance does not produce large errors. In practice it is sufficient to use a resistance alloy of low temperature coefficient.

In addition to simplicity both theoretical and practical, advantages of this method of proving Ohm's law are that it avoids the use of resistances or other apparatus calibrated on the assumption that Ohm's law is true; and, furthermore, it gives results in which the experimental errors are small in comparison with the differences of the quantities measured and hence tends to impress the beginner with the real exactness of Ohm's law.

SHANNON PHYSICAL LABORATORY,
COLBY COLLEGE,
DECEMBER, 1924.